REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE Technical Papers	3. DATES COVERED *(From - To)*
4. TITLE AND SUBTITLE Please see attached		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 1011
		5e. TASK NUMBER 0046
		5f. WORK UNIT NUMBER 346204
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048		8. PERFORMING ORGANIZATION REPORT
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S NUMBER(S) Please see attached

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20030116 042

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	A		Leilani Richardson
Unclassified	Unclassified	Unclassified			19b. TELEPHONE NUMBER *(include area code)* (661) 275-5015

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

MEMORANDUM FOR PR (In-House Publication)

FROM: PROI (TI) (STINFO) 19 Jun 2000

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2000-135**
Mead, F., "Beamed Energy (Laser) Propulsion"

AIAA Short Course **(Statement A)**
(Huntsville, AL, 21-22 Jul 2000) **(Submission Deadline: 9 Jun 2000)**

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.
Comments:_______________

Signature _______________ Date _______________

2. This request has been reviewed by the Public Affairs Office for: a.) appropriateness for public release and/or b) possible higher headquarters review.
Comments: _______________

Signature _______________ Date _______________

3. This request has been reviewed by the STINFO for: a.) changes if approved as amended, b.) appropriateness of distribution statement, c.) military/national critical technology, d.) economic sensitivity, e.) parallel review completed if required, and f.) format and completion of meeting clearance form if required
Comments:_______________

Signature _______________ Date _______________

4. This request has been reviewed by PR for: a.) technical accuracy, b.) appropriateness for audience, c.) appropriateness of distribution statement, d.) technical sensitivity and economic sensitivity, e.) military/ national critical technology, and f.) data rights and patentability
Comments:_______________

APPROVED/APPROVED AS AMENDED/DISAPPROVED

____

LESLIE. S. PERKINS, Ph.D (Date)
Staff Scientist
Propulsion Directorate

BEAMED ENERGY (LASER) PROPULSION
(A Perspective)

by

Dr. Franklin B. Mead, Jr.
AFRL/PRSP
10 East Saturn Blvd.
Edwards AFB CA 93524
Phone: (661)275-5929
E-mail: franklin_mead@ple.af.mil

Outline

- Preliminaries
- Historical Overview
  - The Early Years 1970-1990
- Concepts From The Early Years
  - Project Outgrowth
  - Paraboloid
  - Absorption Chamber
  - Heat Exchanger
- Developments In The 90's
  - Domenstic
    - NASA
    - Air Force (Lightcraft)
  - Foreign
- References

What is Laser Propulsion?

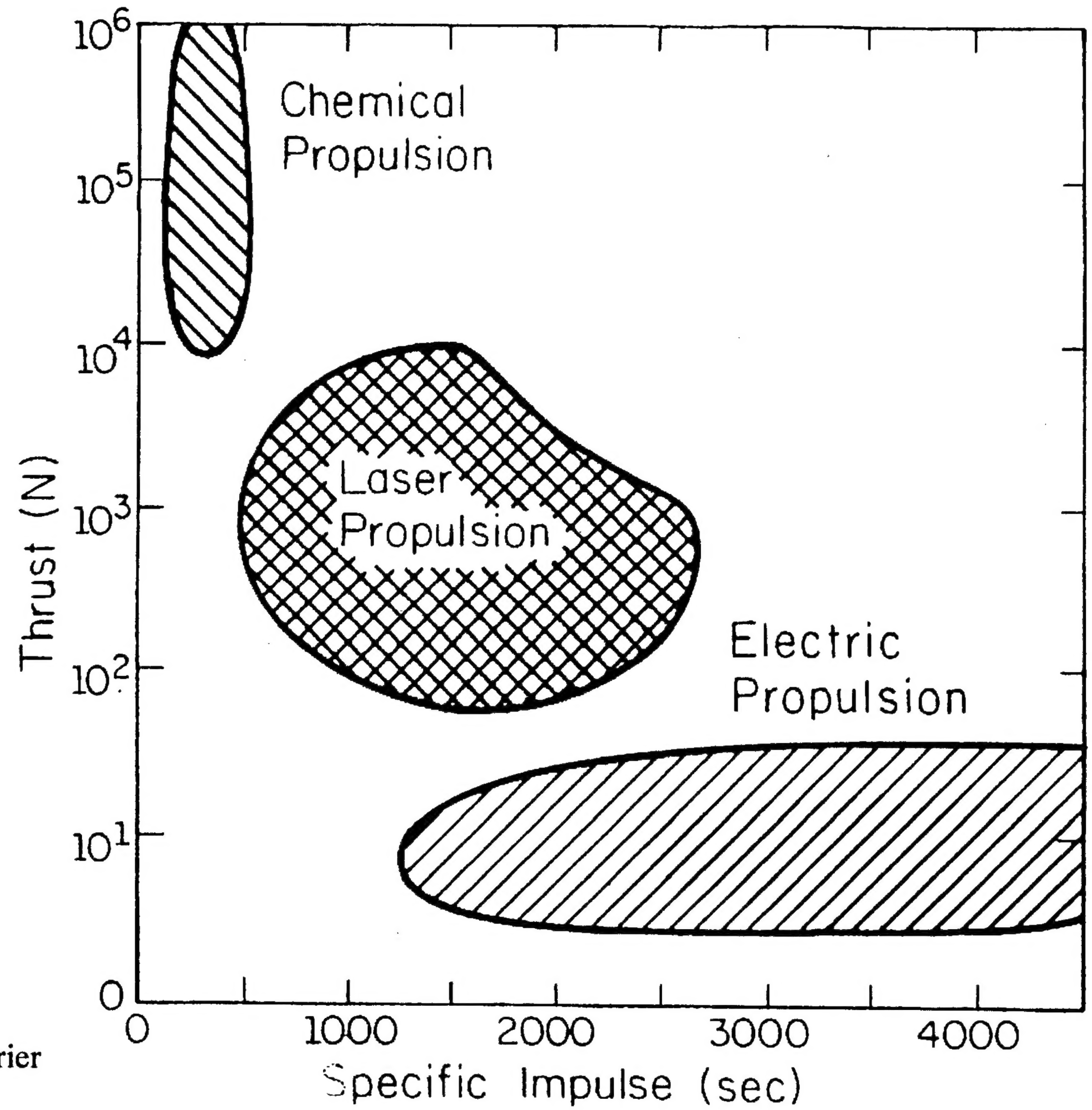
- Propulsion System Using (typically) External Laser Power Source (ground and/or space based)
  - Heats Propelland to Very High Temperatures
  - Provides Energy Source For Electrical Power Generation
  - Provides Direct Photon Force

"Laser propulsion is an idea that may produce a revolution in space technology."
JASON Laser Propulsion Study, Summer 77

Background

- Why Laser Propulsion
  - Decoupled Energy Source
  - High Specific Impulse (Isp) Potential
  - High Thrust Relative to Electric Concepts
  - Avoids the Radiation and Mass Penalties Inherent With Nuclear Propulsion
  - Technical Problems are not Fundamental
  - Econonomic Justification Concluded in Separate Studies by AF, NASA, & DARPA
- Mission Potential
  - Low Cost Access to Space
  - Orbit Raising
  - Kinetic Kill Vehicles (KKV)
- Problems
  - Lacks Complete Demonstration After 31 Years From Conception
  - Reduced Funding for Demonstration
  - Low Interest

Laser Propulsion Performance Relationships*



*U. Of Illinois report by Dr. Krier
Under AFOSR Contract

Propulsion Relations

Rocket:

F = Thrust

_ = Weight Flowrate

g = Gravitational Acceleration

- $I_{sp} = F/\_$ ← Specific Impulse (s)
- $P = \_gFI_{sp}$ ← Exhaust Power (J)

why are these out in the middle?

Pulse Jet:

I = Impulse Bit (N-s/pulse)

E = Total Energy in a Laser Pulse (MJ/pulse)

t = Pulse Length or Width (s)

f = Pulse Frequency(s^{-1})

- η (CC or C_m) = I/E — Coupling Efficiency (N-s/MJ)
- $F = \eta(E/t) = I/t$ ← Thrust per Pulse (N)
- $F_{av} = f(Ft) = f(\eta E) = fI$ ← Average Integrated Thrust
- $F_{lbs} = F_N/4.45$ ← Conversion to Pounds of ? Thrust

Brief History

Beamed Energy Rockets

- Microwaves – Willinski (1959)
- Lasers – Light Sails – Forward (1962)
  - Rockets – Geisler (1969), Kantrowitz (1972)

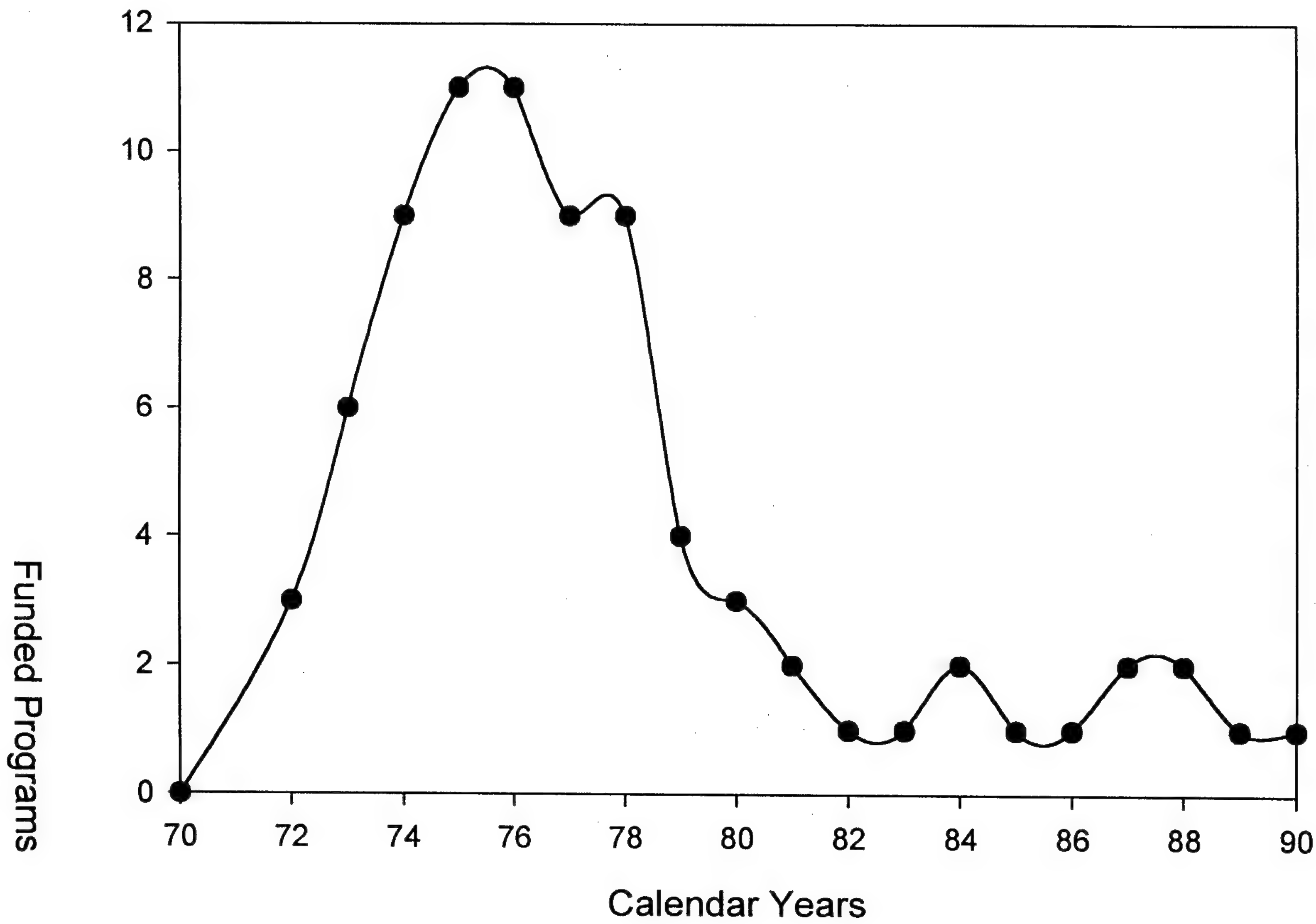
Propulsion Activities

- AFRPL 1972 – Inhouse (Project Outgrowth Report) & Contracted Efforts – TRW, PSI
- NASA 1972 – NASA Lewis Inhouse & Contracted Efforts – PSI, Lockheed, Rocketdyne
  - 1977 – NASA Marshall Inhouse & Contracted Efforts – PSI, U.S. Army Micom, Lockheed, BDM, UTSI, UAH
  - 1977 - JPL – System Studies – Lockheed, Boeing
- DARPA 1977 – AVCO Everett Study
- AFOSR 1983 – Contracted Efforts – Penn State, PSI, UTSI, U. of Illinois
- SDIO 1986 – LLNL Inhouse & Contracted Efforts – AVCO, Spectra Technologies, NRL, PSI, RPI

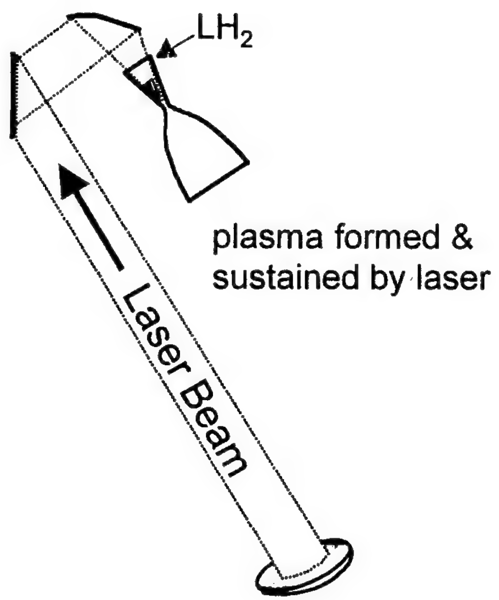
Major Laser Propulsion Funding Agencies and Contractors
The Early Years: 1972-1990

Funding ↓ / Contractors →	Physical Sciences Inc.	AVCO Everett Research Lab. Inc.	Mathematical Sciences NW Inc.	Lincoln Lab.	Lockheed Missiles & Space Co.	TRW	Rocketdyne	Lawrence Livermore Natl. Lab.	SRI International	Tennessee Space Institute	United Technology Research Ctr.	U. of Illinois	Photonic Associates	Hughes Research Lab	JPL	Redstone Arsenal	Aberdeen Proving Ground	Harry Diamond Lab.	Battelle Lab.
AF Rocket Propulsion Lab.	80/81					75/76					77/79								
AF Office of Scientific Research	83/84									85/91		87/88							
SAMSO (Los Angeles AF Station)		73																	
NASA/MSFC	78/80				78														
NASA/LEWIS	74/77	76	79		76/78		75/77						74/75						
NASA/JPL														75	84				
DARPA (ARPA)	76/82	74/78	75	76					76/77		73/74								73/75
US Atomic Energy Commission								74											
US Energy Research & Dev.								75											
Army																77	74	75	
SDIO								87/90											

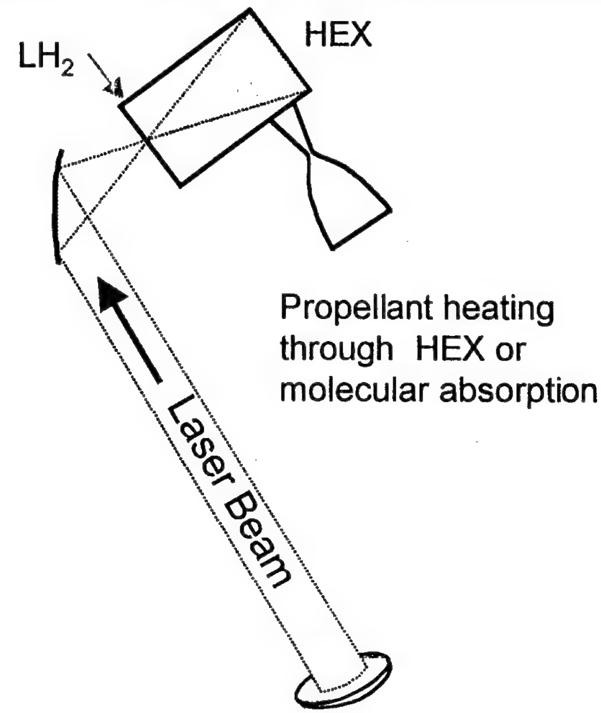
Laser Propulsion Interest During the Early Years



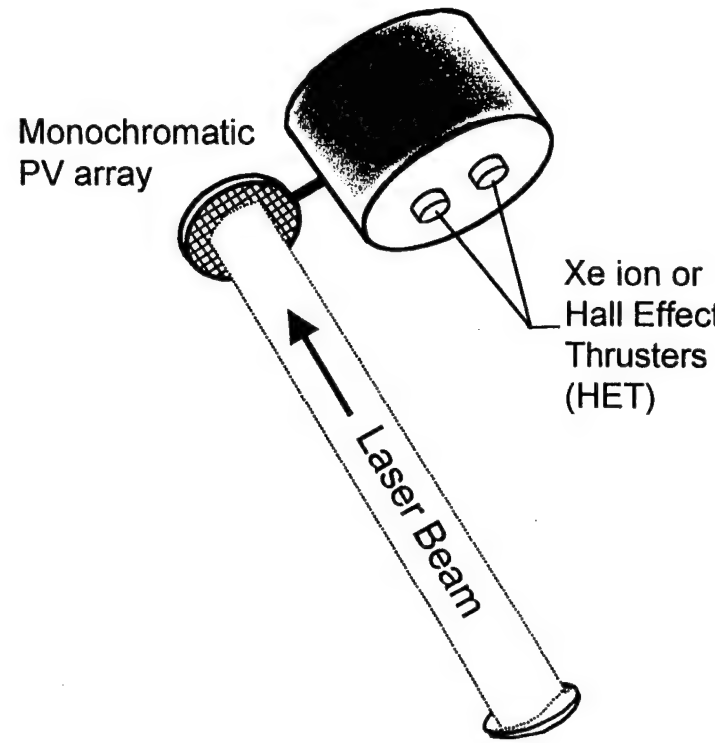
Laser Propulsion Concepts*



Laser Plasma
(Is = 1000 to 1500 sec)



Laser Thermal
(Is = 700 to 1100 sec.)

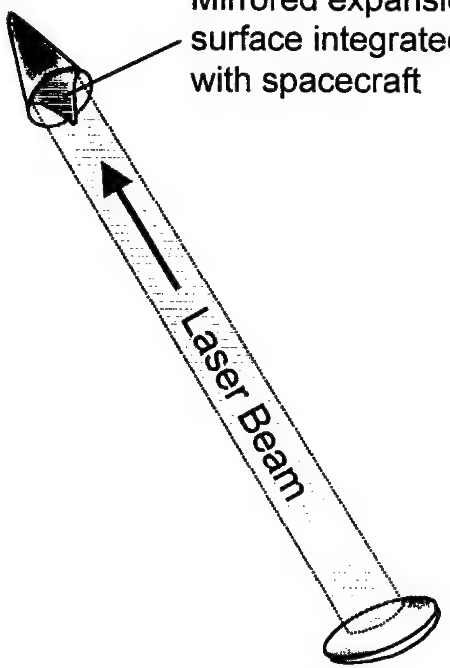


Laser Electric
(Is = 1200 to 4000 sec.
at low thrust)

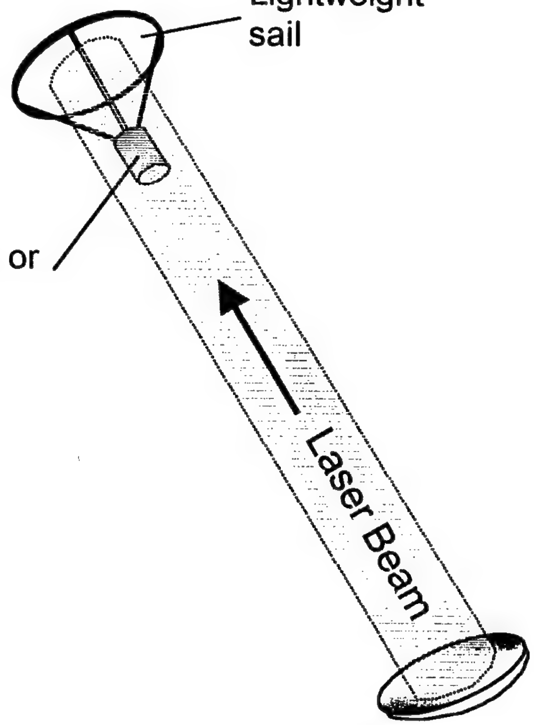
***Taken from Mr. Jim Shoji, Rocketdyne, Boeing Co.**

Laser Propulsion Concepts* (cont'd)

Concluded



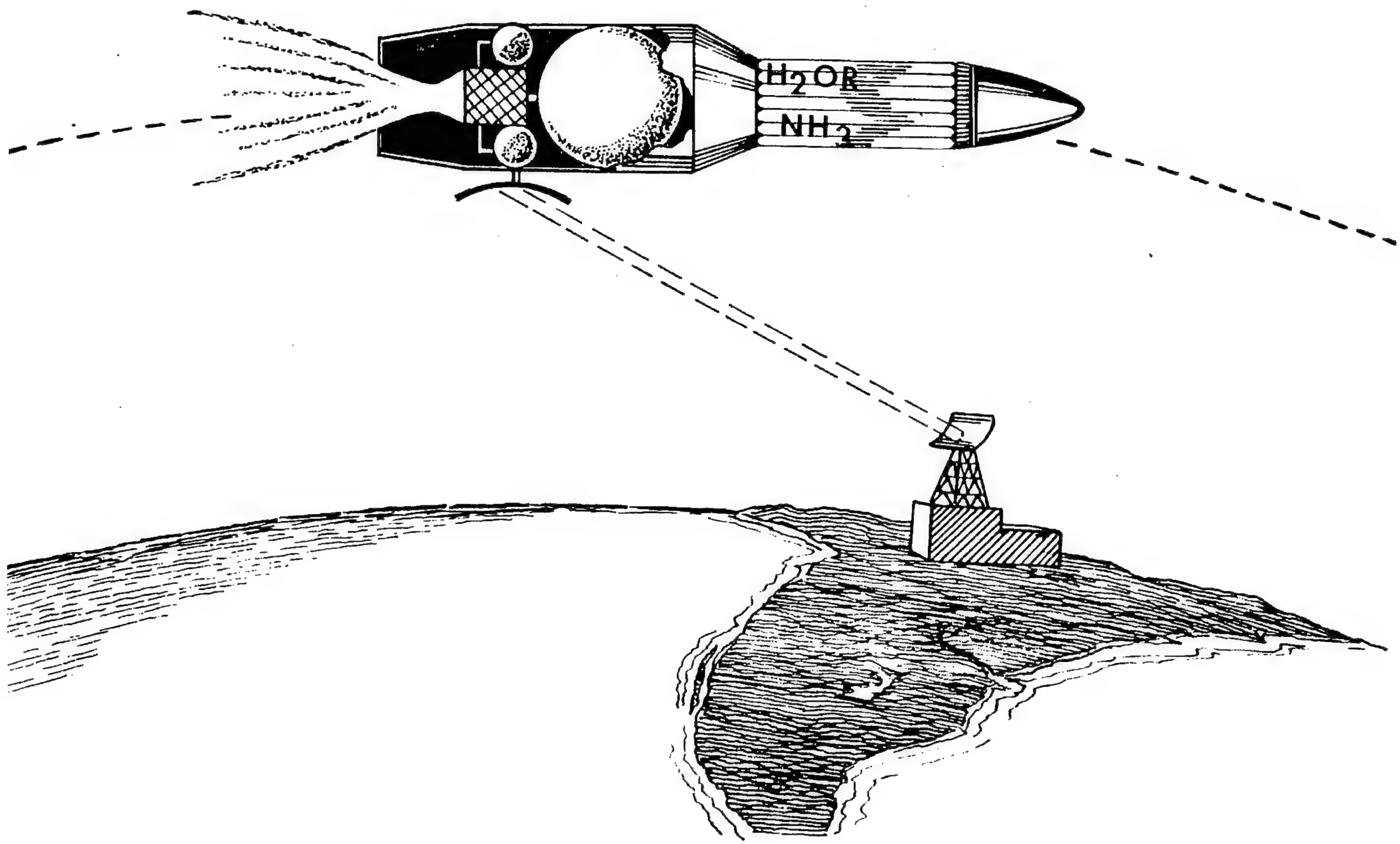
Laser Detonation
(Isp: Essentially infinity in air)



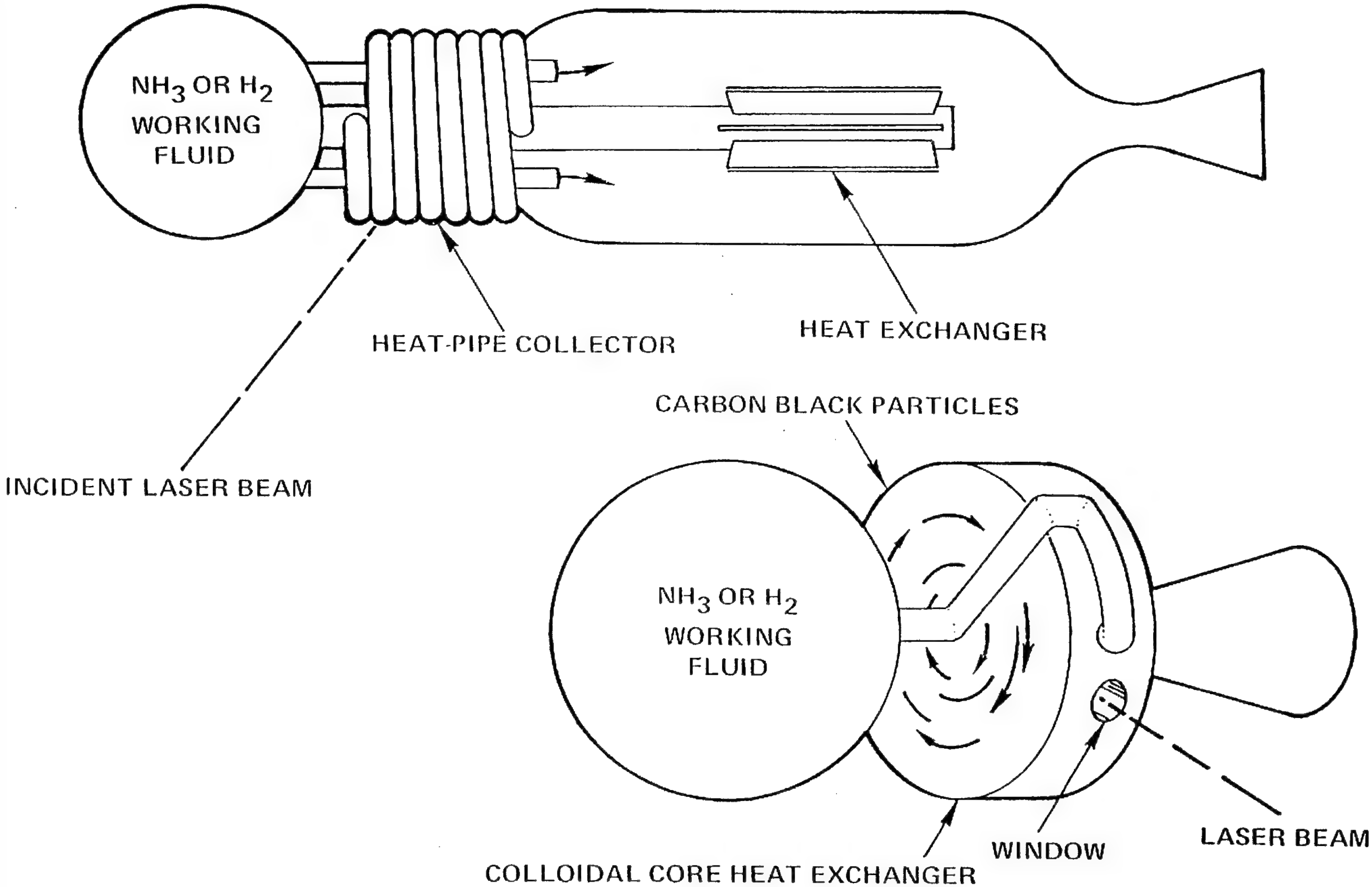
Laser Sail
(Isp: Essentially infinity)

*Taken from Mr. Jim Shoji, Rocketdyne, Boeing Co.

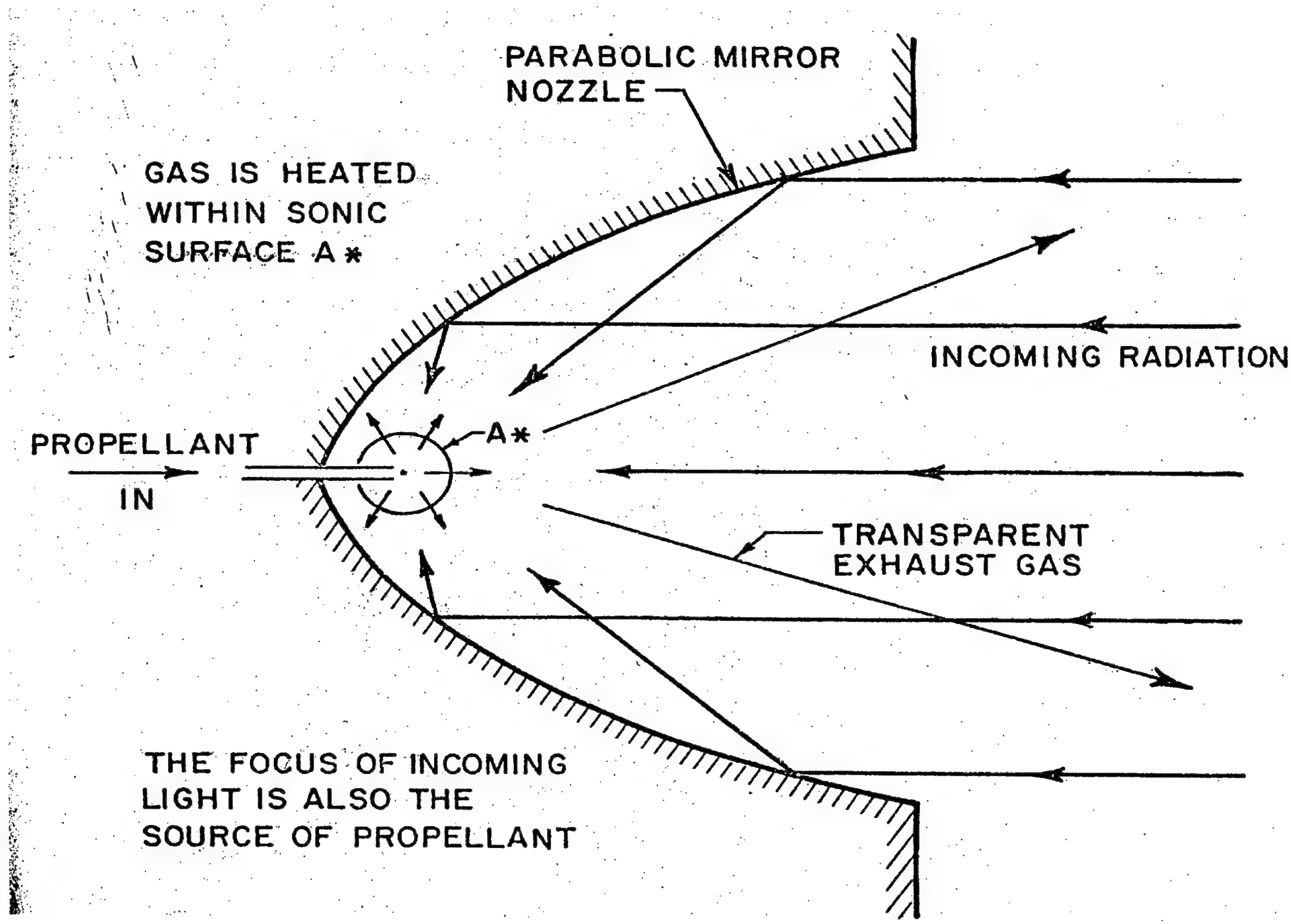
Laser Propulsion (Project Outgrowth)
(Circa 1970)



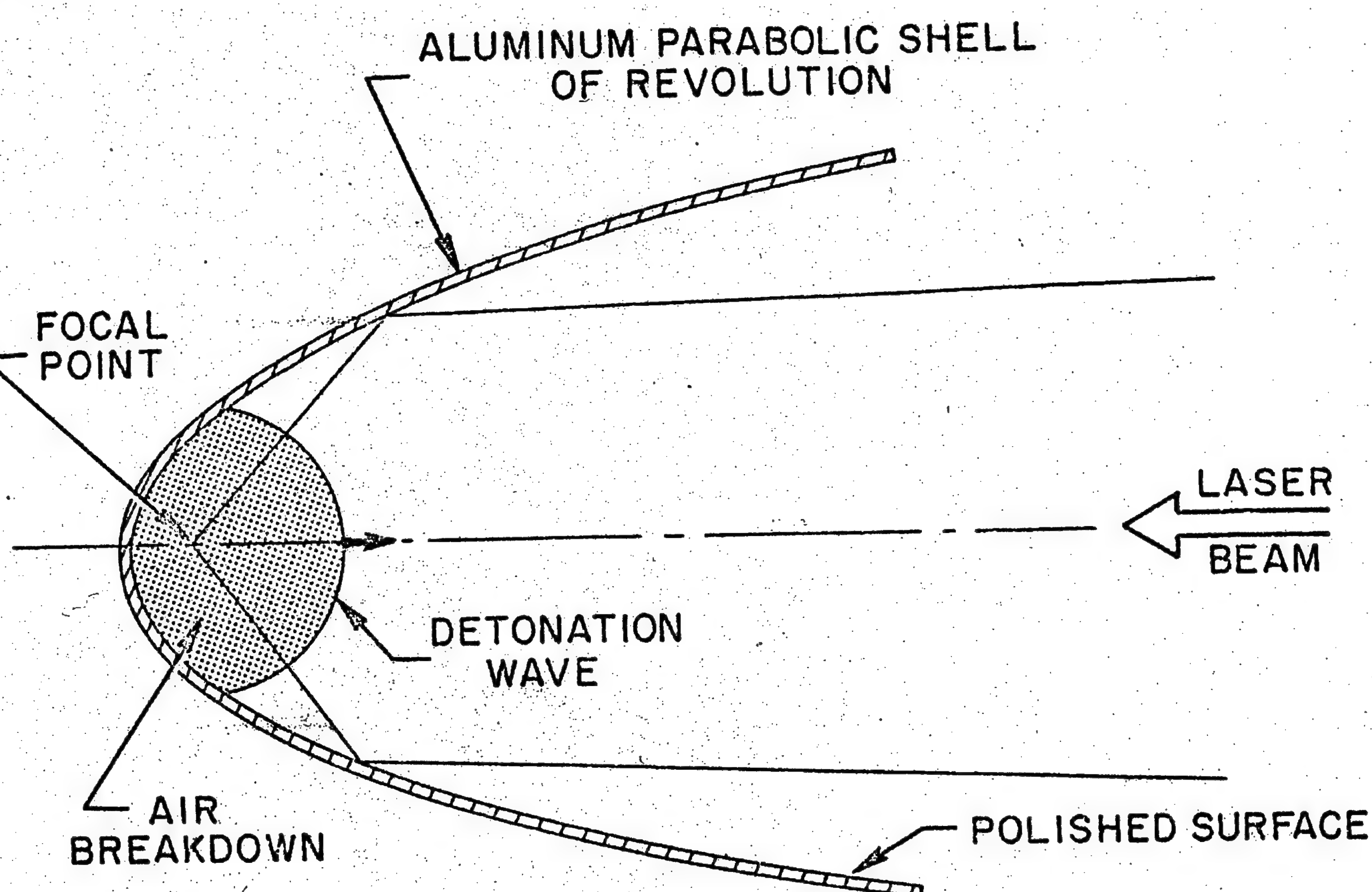
Laser Propulsion (Project Outgrowth) (Circa 1970)



AVCO Liquid Propellant Rocket Using CW Laser (Circa 1973)



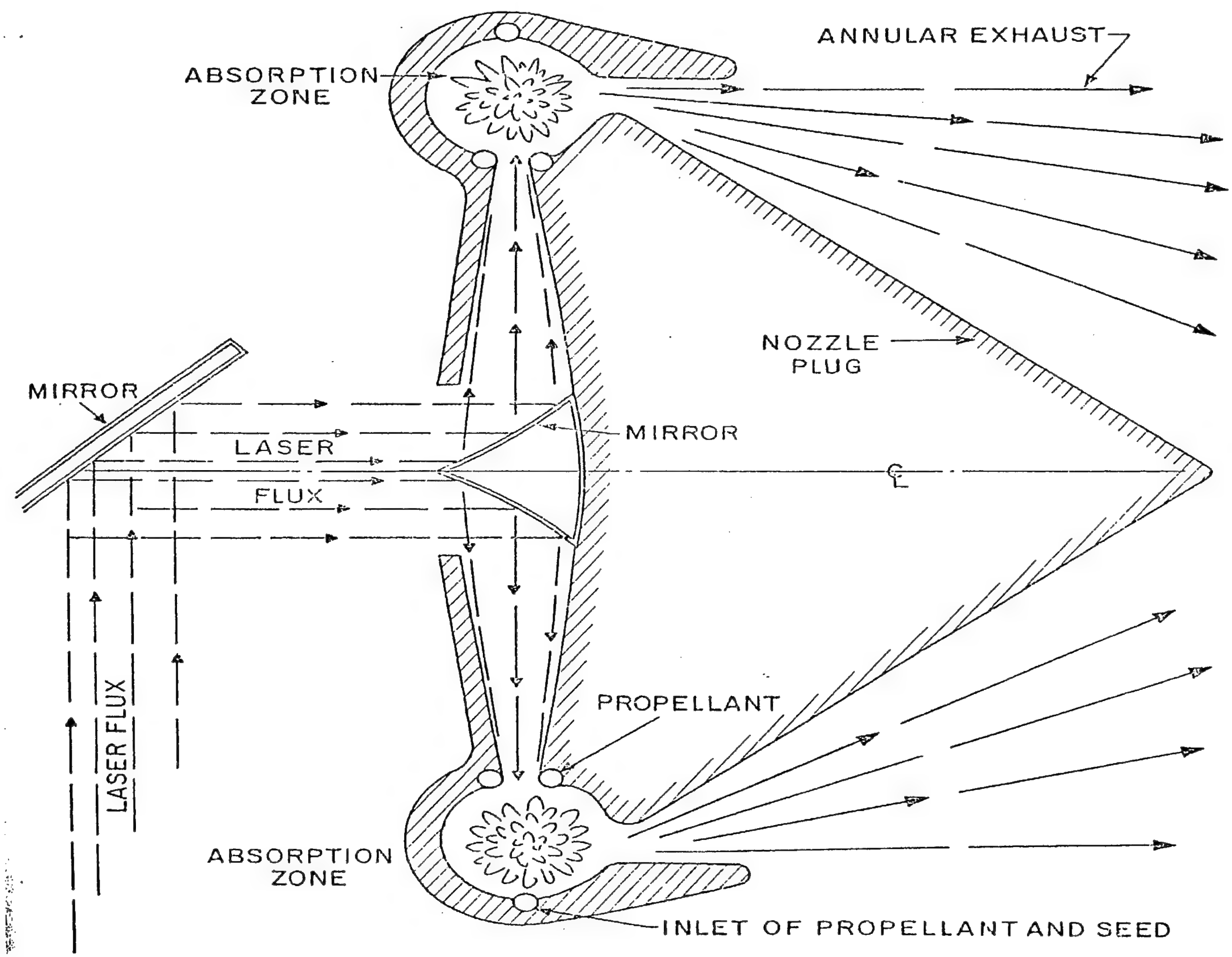
AVCO Laser Pulsejet
(Circa 1973)



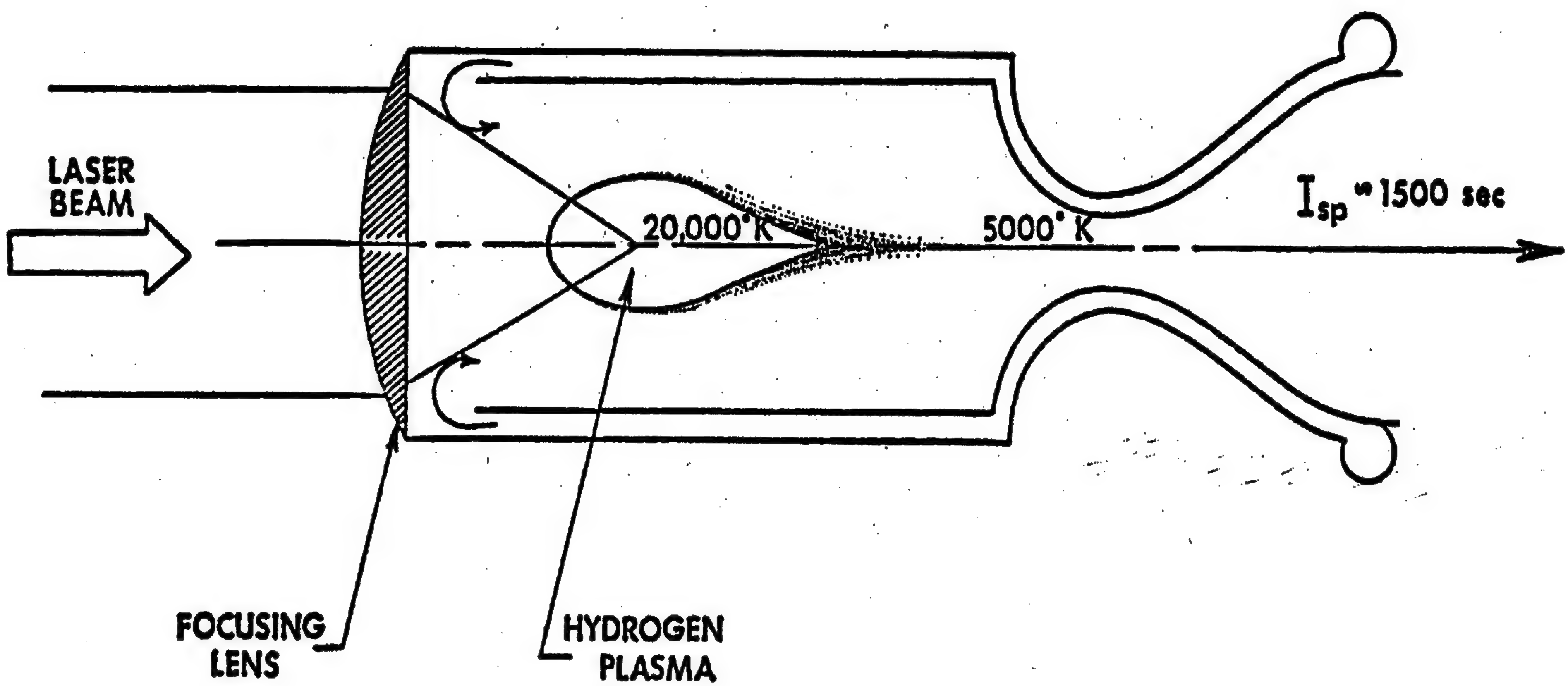
AVCO Advanced Laser Rocket

Toroidal Combustion Chamber, Plug Nozzle

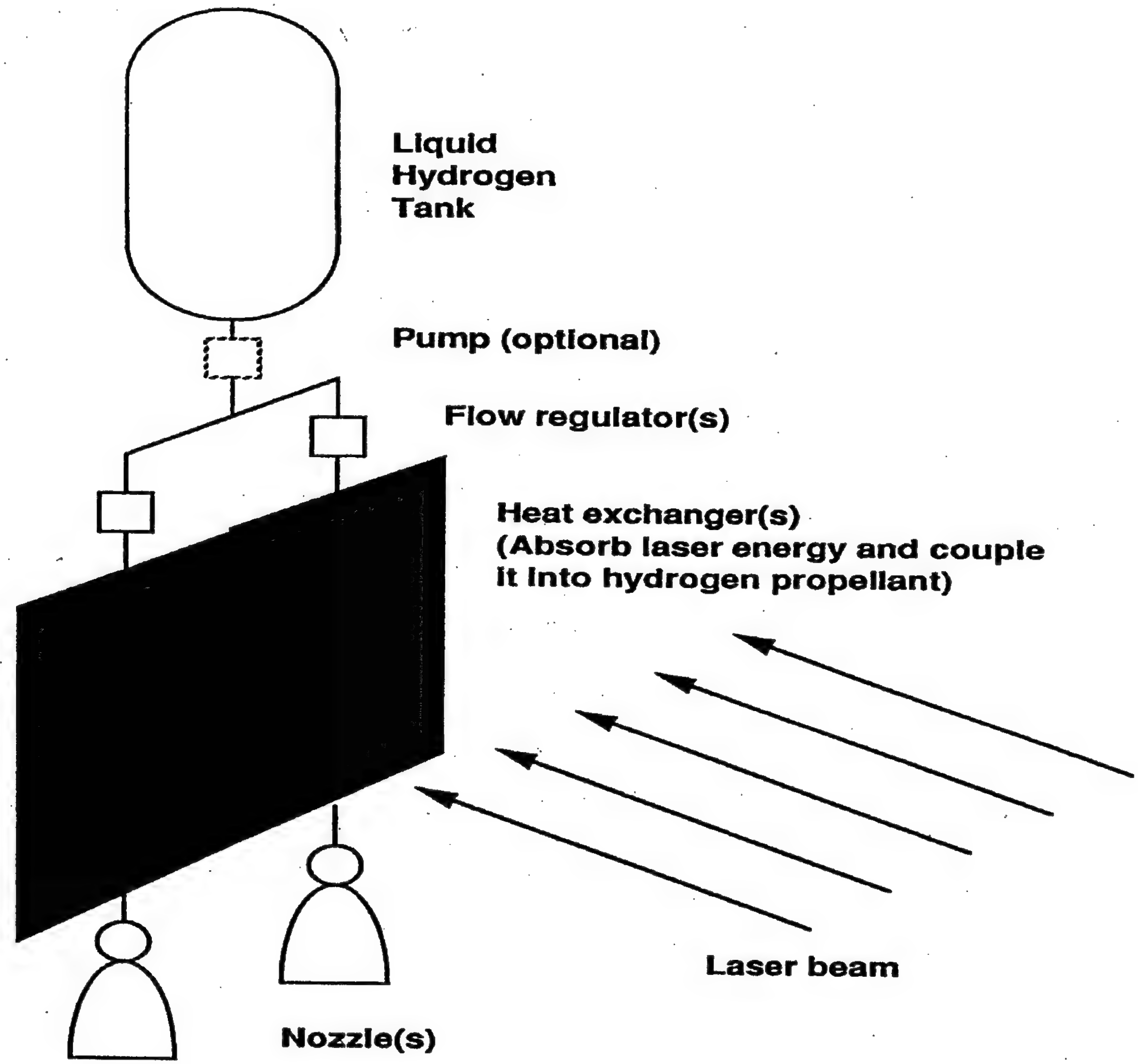
(Circa 1973)



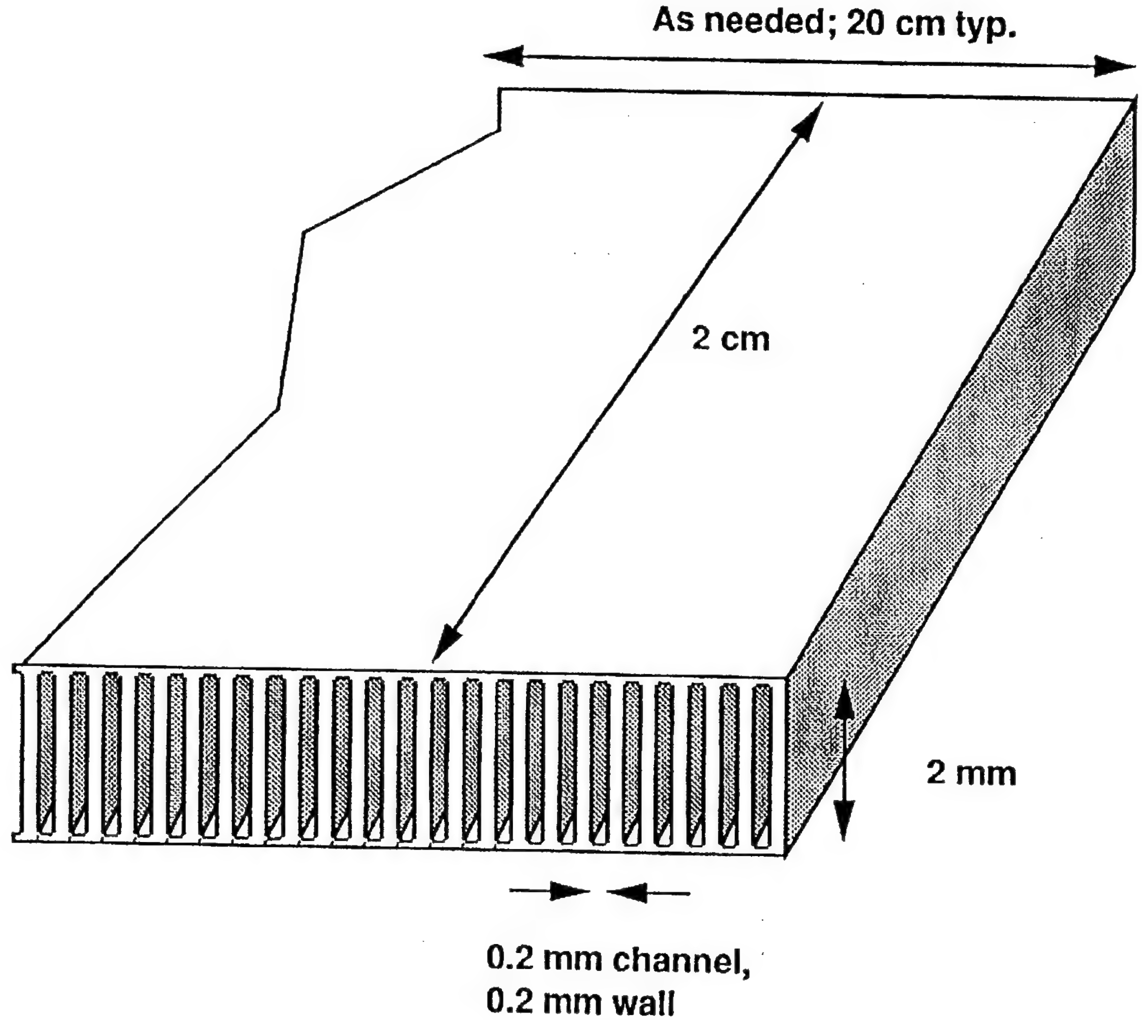
"Keefer" Laser Absorption Chamber
(Circa 1986)



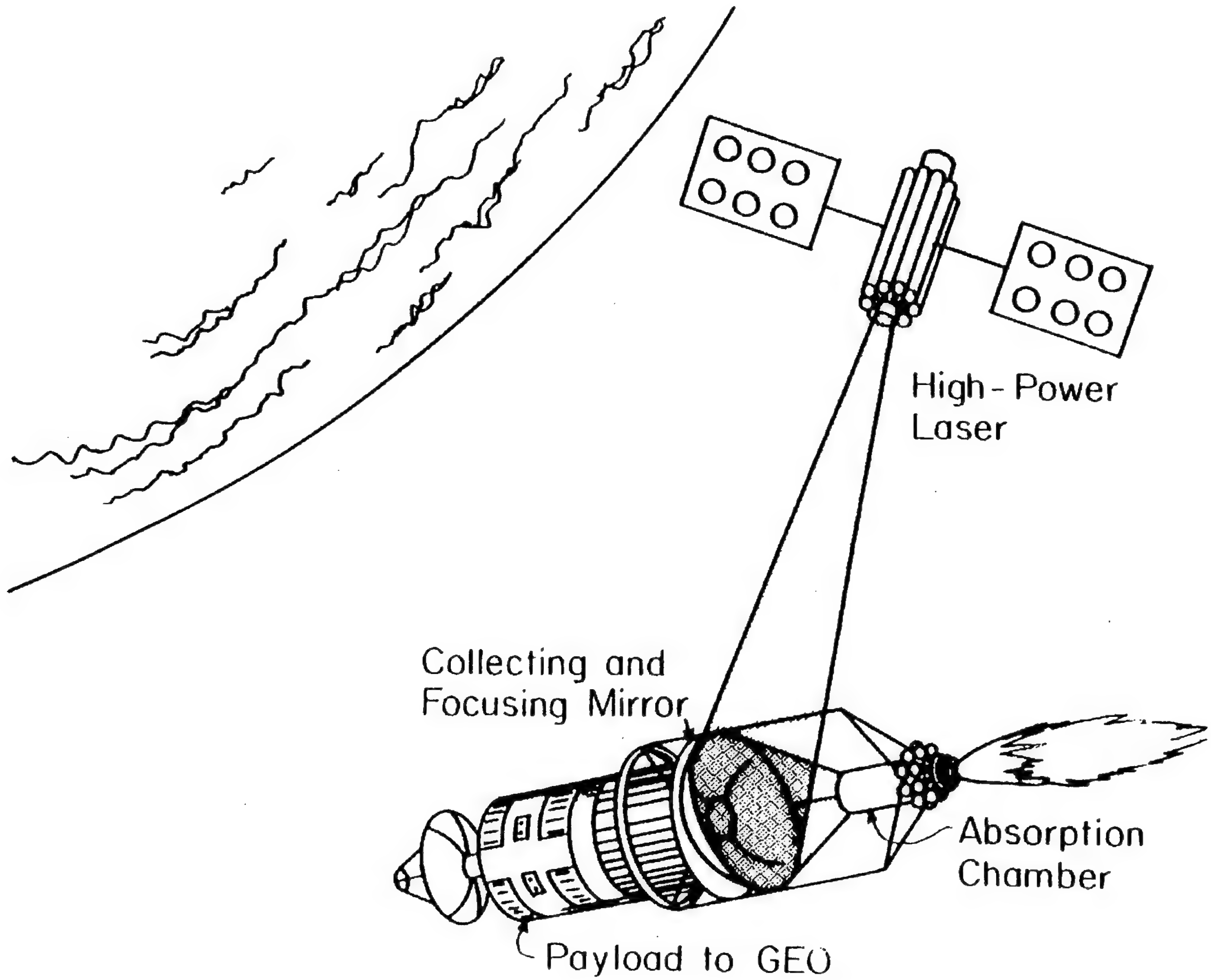
"Kare" Heat Exchanger Concept
(Circa 1992)



Kare's Microchannel Heat Exchanger Structure



University of Illinois Laser Propulsion Concept (Circa 1987)



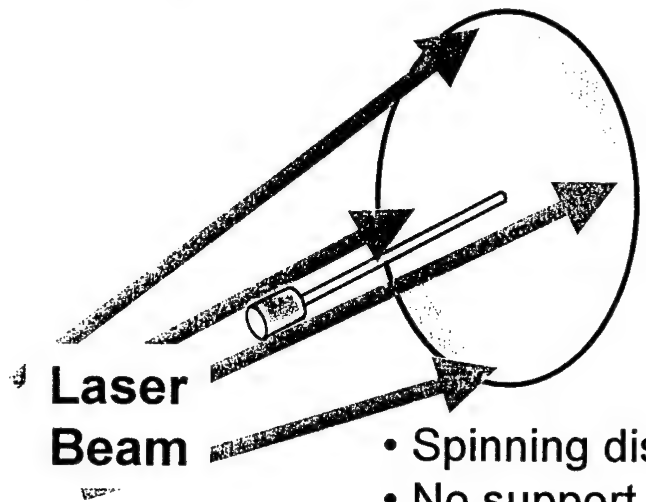
Laser Sail Propulsion

- **Features**
  - Large, lightweight structures
  - Very, very high power space-based laser
  - Low thrust and low acceleration
  - High spacecraft velocity potential (0.1 to 0.5c)
- **Performance Potential**
  - Specific Impulse : Infinite
  - Thrust : Dependent on laser power,flux, sail area, and efficiency

space after comma

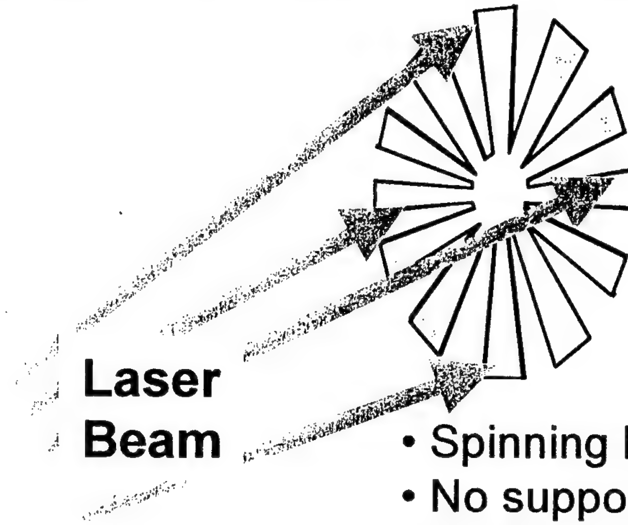
- **Technology Status**
  - Concepts developed
  - Synergistic with solar sail technology
    - Russian solar mirror ZNAMIA deployed in space (1993)
    - On-going NASA/JPL efforts
    - Other university/small group/industry activities
- **Issues**
  - Very, very high power space-based laser
  - Fabrication and deployment of very large structures (lens and sail)
  - Verification of multi-function laser sail sections

Laser Sail Design Concepts



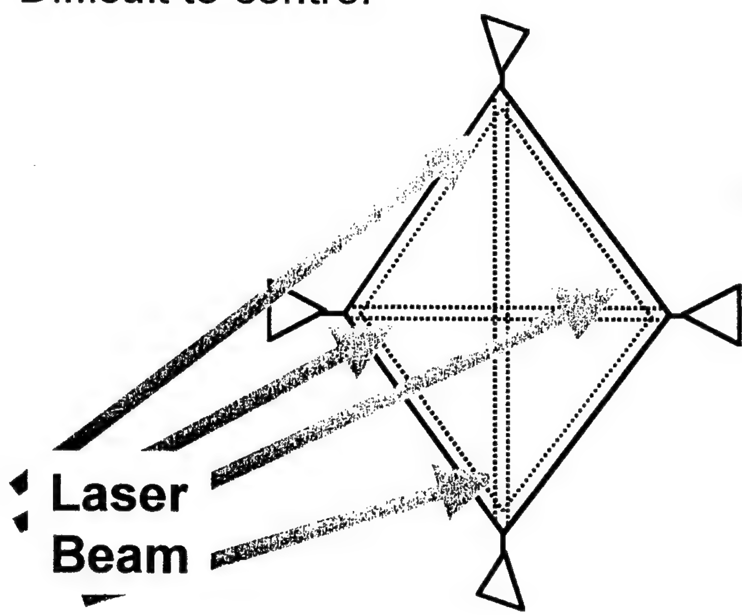
Disc Sail

- Spinning disc
- No support structure
- Difficult to control



Heliogyro Sail

- Spinning blades
- No support structure
- Control by pitching blades



Rectangular Sail

- Non-rotating
- Structurally supported
- Control - solar pressure vanes

Developments in the 90's

- NASA/MSFC
  - Financially Contributed to the Air Force program during FY 97 & 98.
  - Initiated their own program in FY 99
    - FY 99 Study Phase
    - Initiated Testing in FY 2000
    - Concepts include parabolic pulsejet, Lightcraft, & "Phipps" laser concept.
- Air Force
  - Lightcraft Development Program Started FY 96
  - The AFRL and NASA/MSFC have a Memorandum of Agreement (MOA) to work together on the Lightcraft.
- German parabolic pulsejet tests conducted in 1999.

Laser Propulsion At MSFC

By

Mr. Sandy Kirkindall

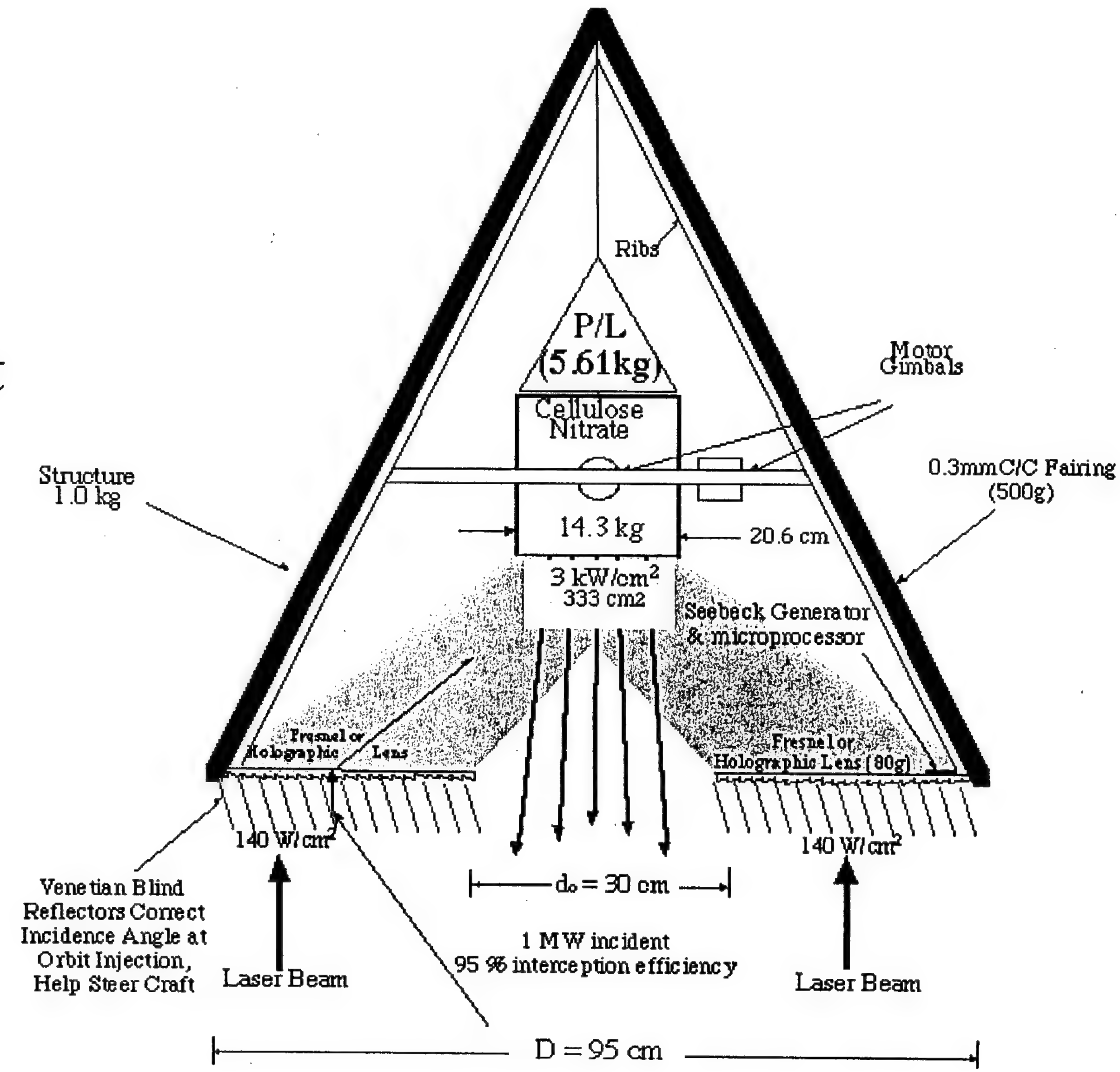
NASA/MSFC, TD40

Bldg. #4666

Huntsville AL 35812

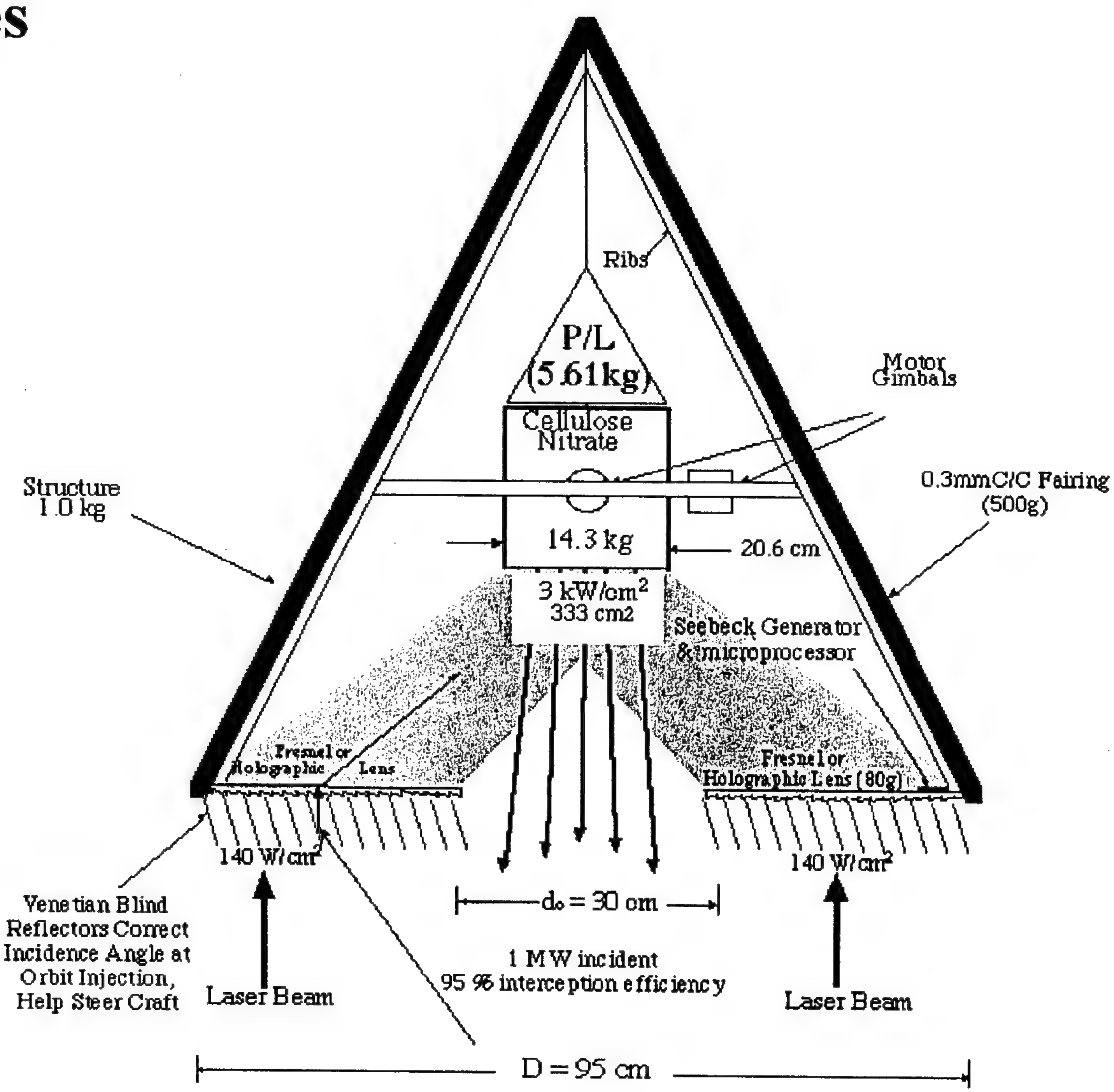
Phipps/NASA Design

- D/L=1 optimizes
  - Drag
  - Center of thrust
  - Jet/lens clearance
- Heat shield dumped at 120km
- "Venetian blinds"
  - For orbit insertion
  - For partial steering

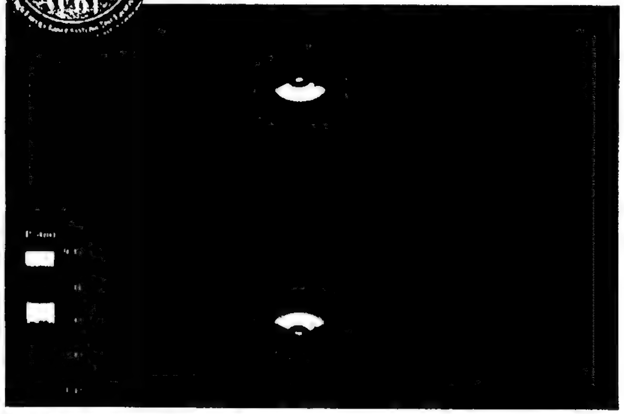


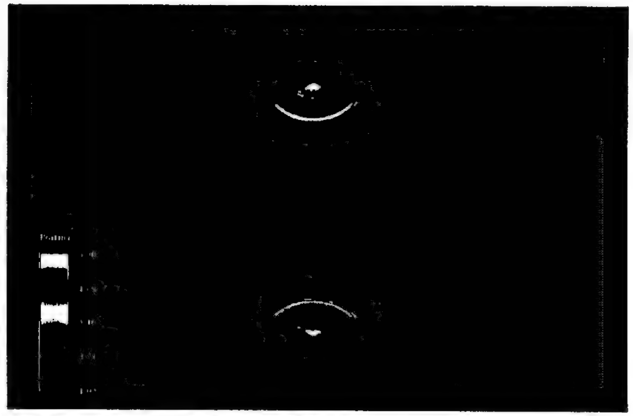
Phipps/NASA Design (Cont)
Concluded

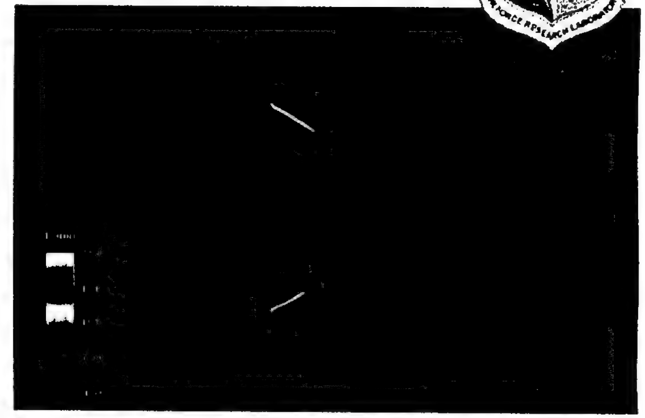
- Fresnel lens concentrates light
- Seebeck generator provides 100W system power
- space or dash?
- μprocessor controls actuators

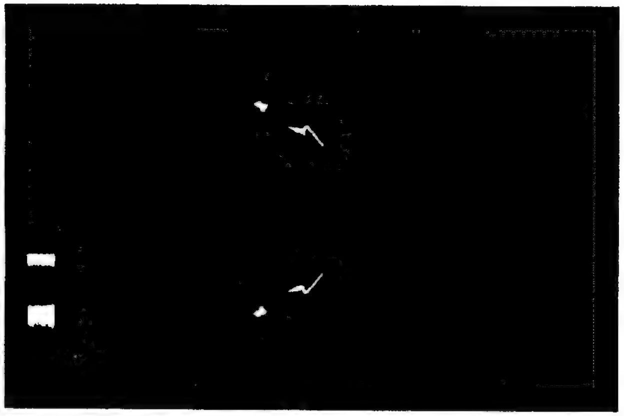


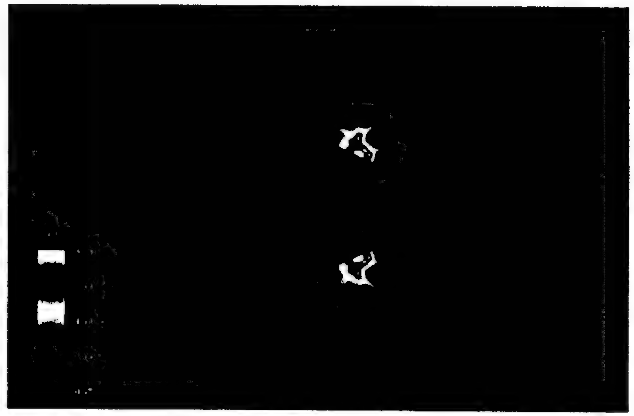
NASA CFD Studies of Lightcraft Pulse Dynamics

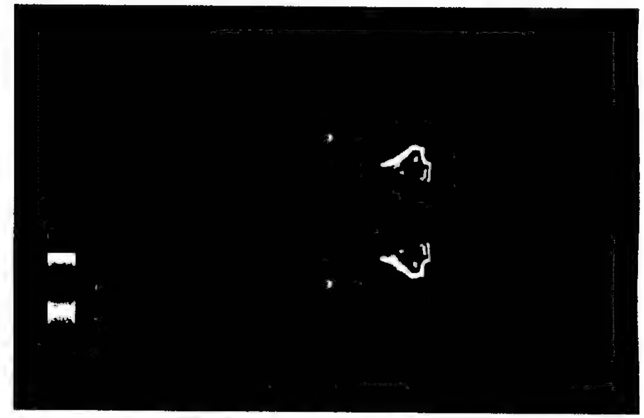

10 usec

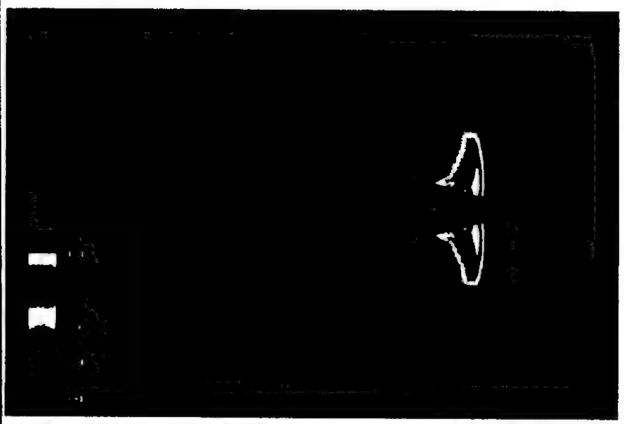

20 usec


30 usec


40 usec

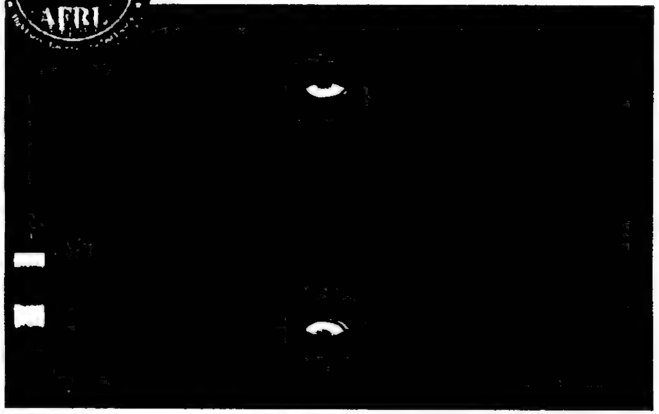

60 usec


80 usec

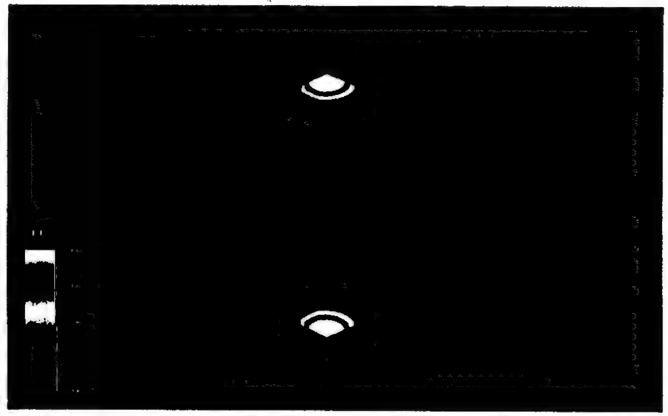

122 usec

PRESSURE (ATM)

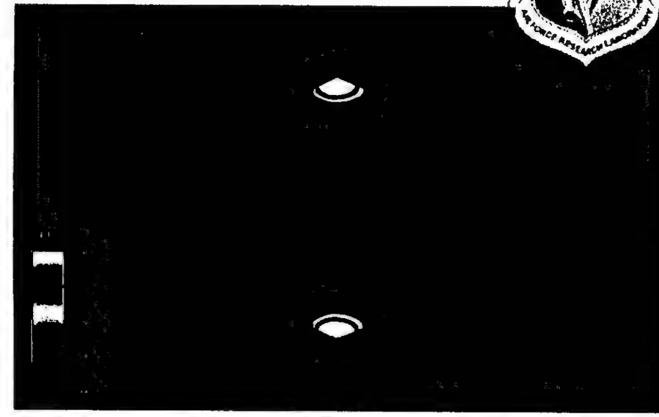
NASA CFD Studies of Lightcraft Pulse Dynamics



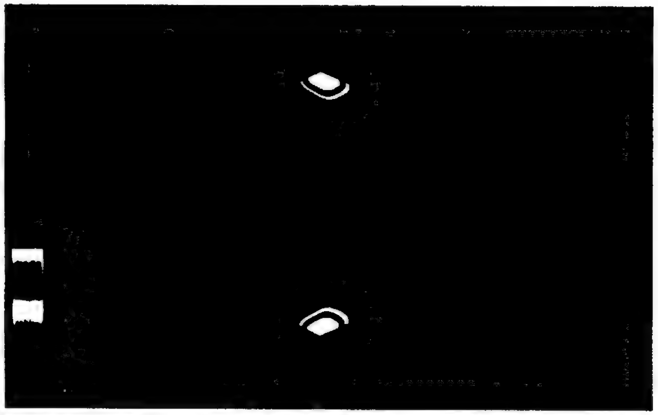
10 usec



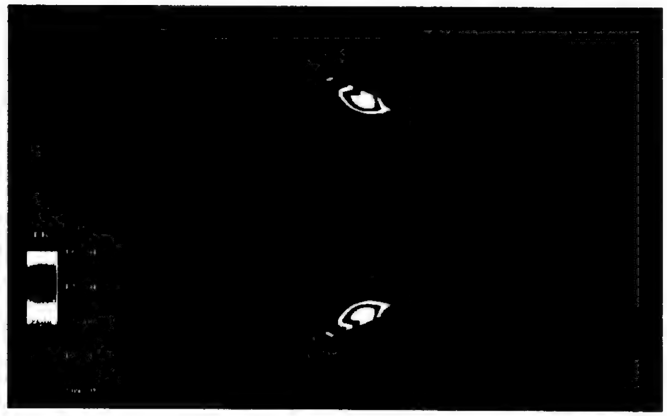
20 usec



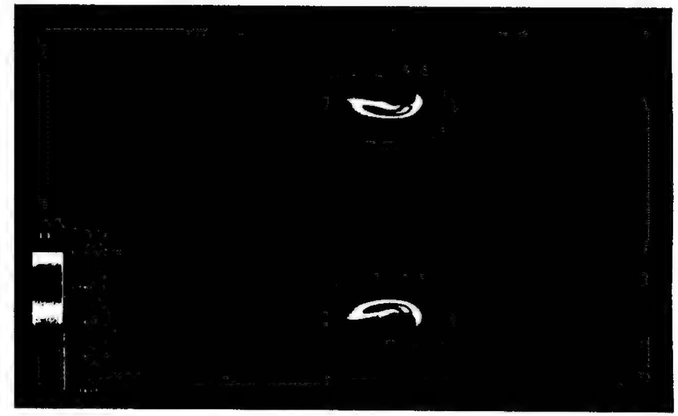
30 usec



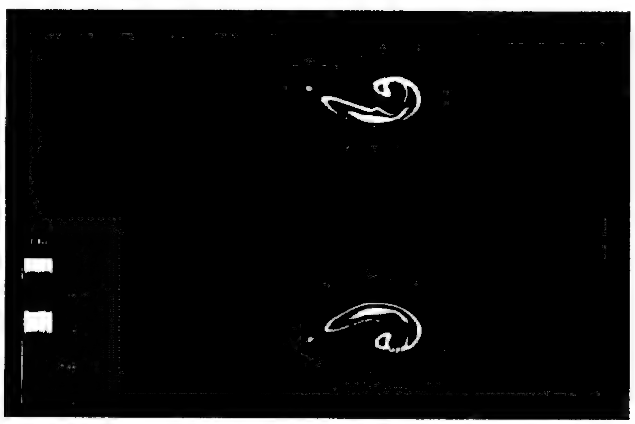
40 usec



60 usec



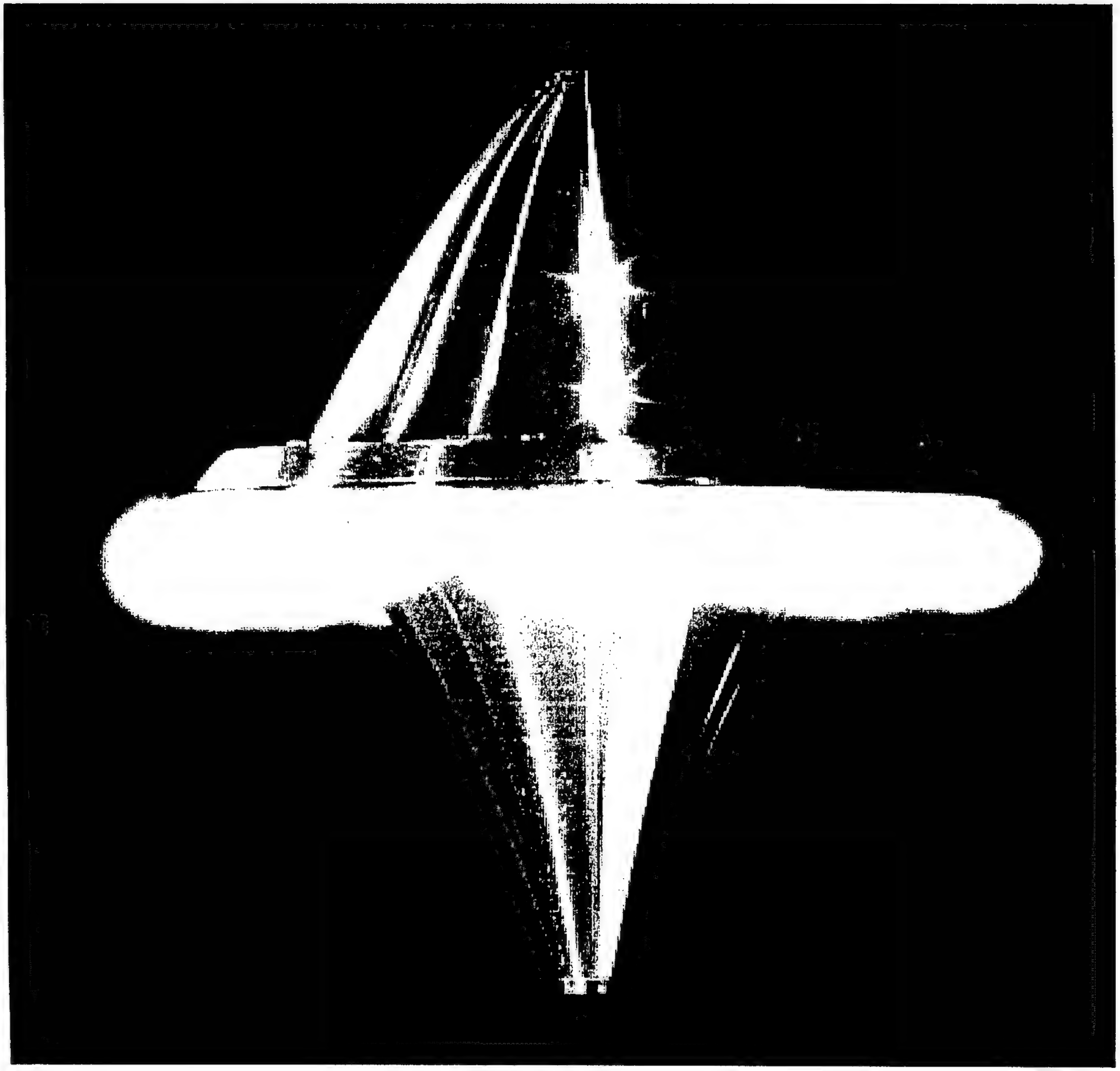
80 usec



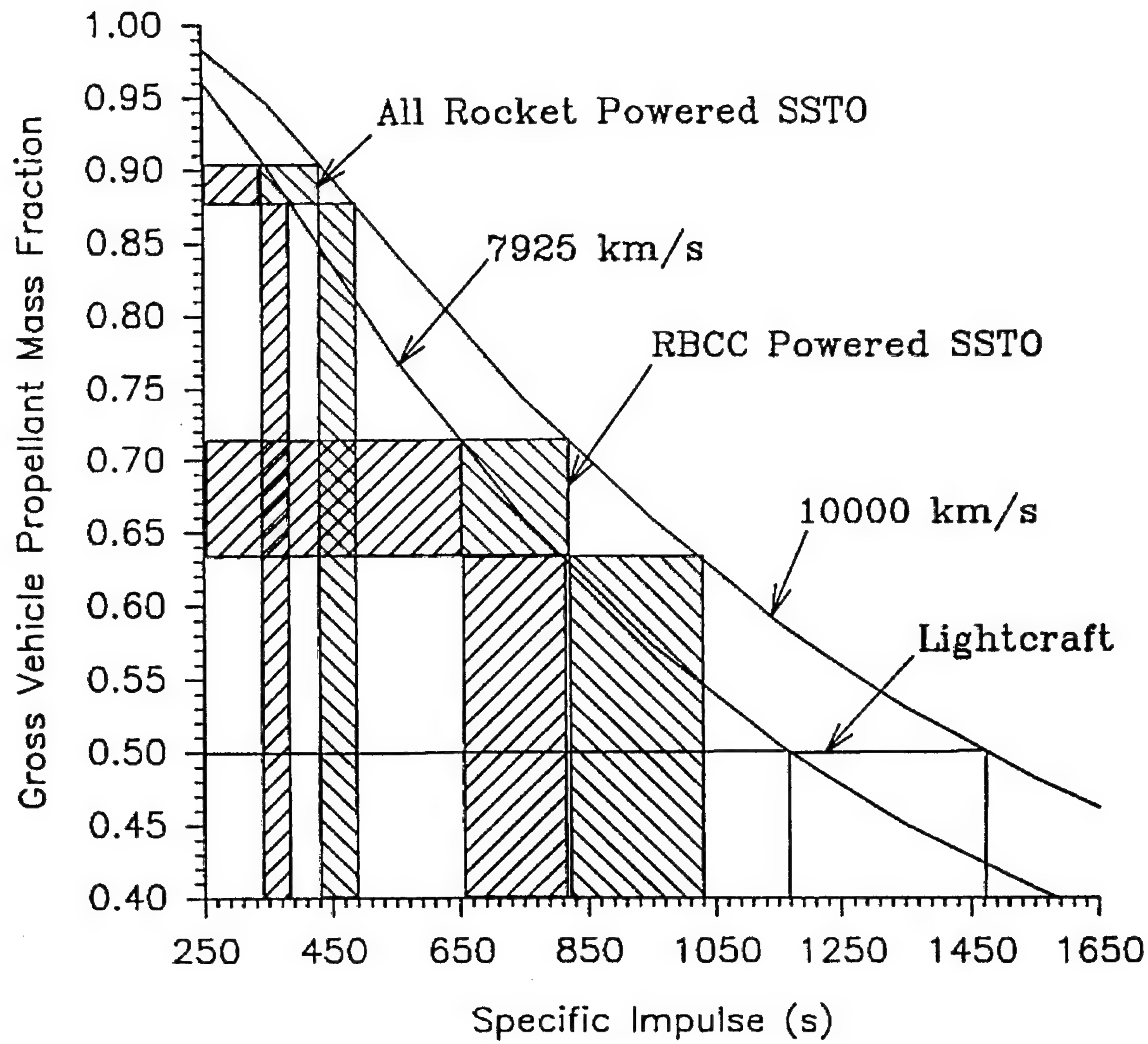
122 usec

TEMPERATURE (K)

LASER LIGHTCRAFT DEVELOPMENT PROGRAM



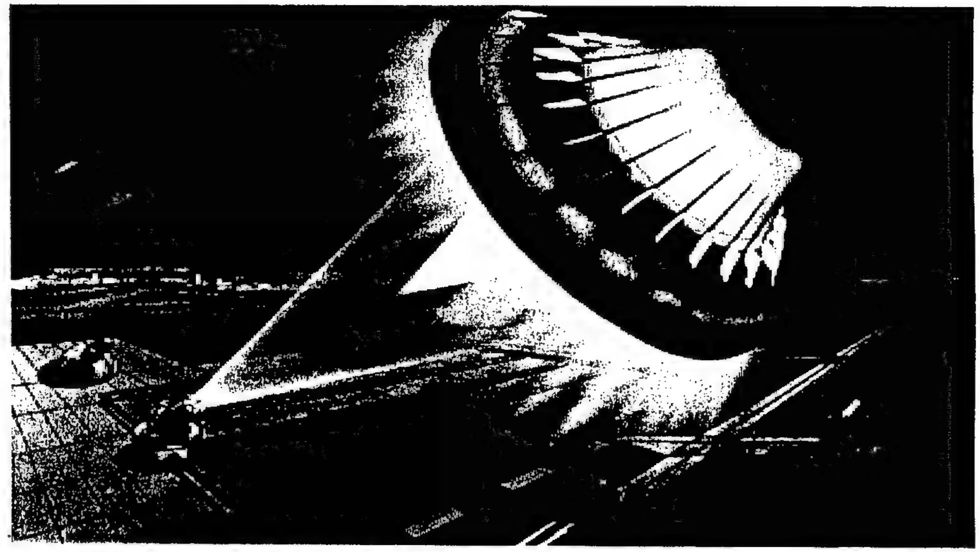
The "Rocket Equation" Applied to Single-Stage-to-Orbit (SSTO) Space Transportation Concepts



LOW COST ACCESS TO SPACE

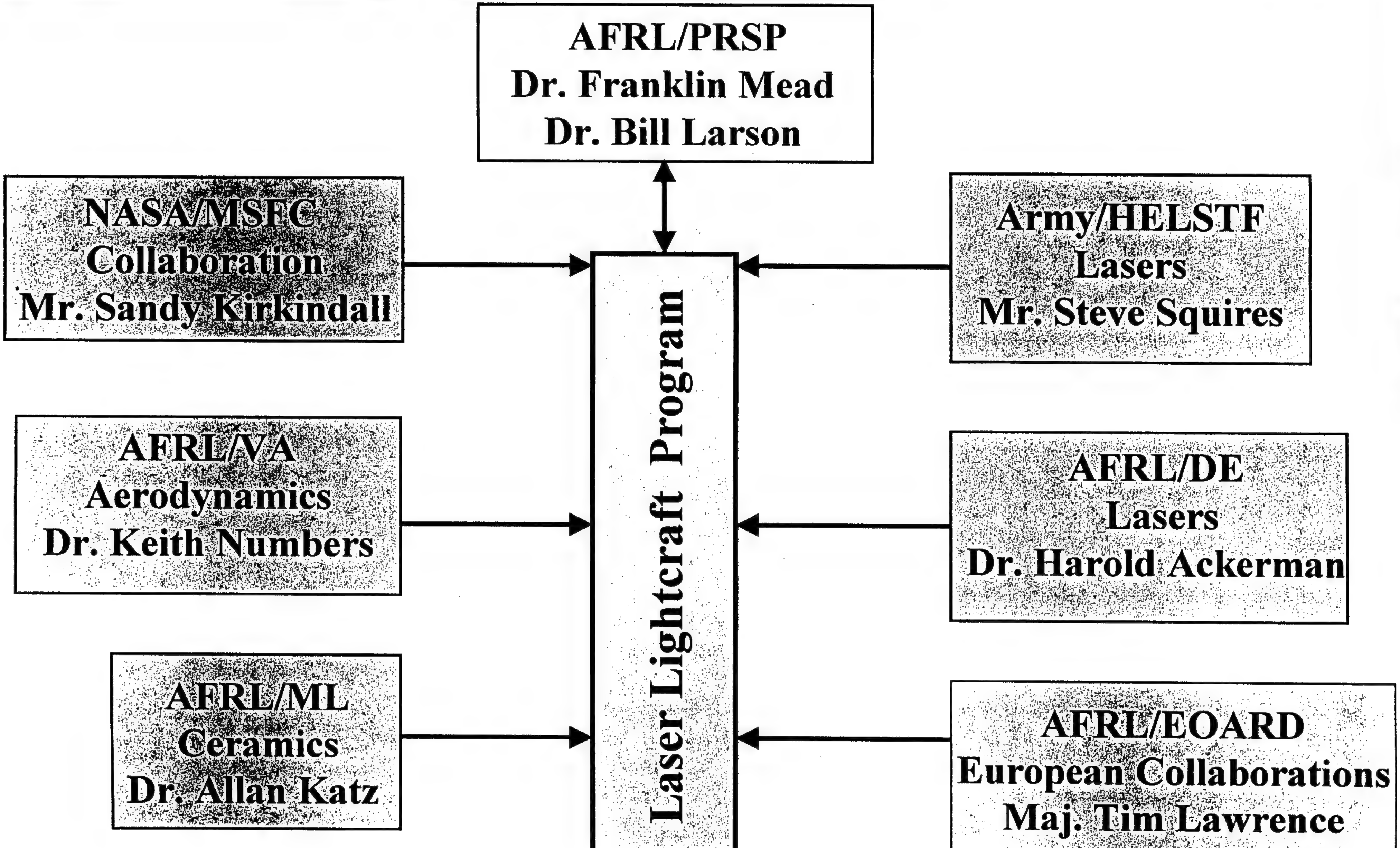
Unique Features

- Laser-Propelled Beam Rider
  - Decoupled Energy Source (1 MW class infrared G/B laser)
  - Single-Stage-to-Orbit (~2 kg initial weight; Mf=0.5)
  - Very High Isp (Airbreathing to M=5 at 30 km; 1,000 to 3,000 s in space with H_2)
  - Combined-Cycle Pulsed Detonation Engine

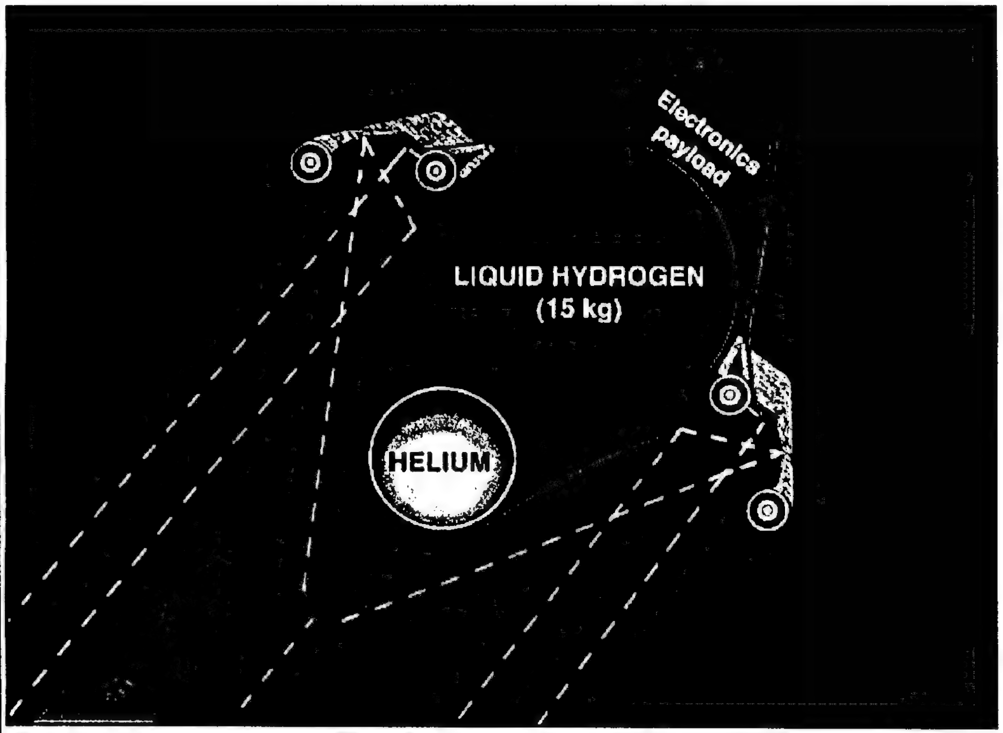


- Multiple/Shared Functional Components
- One-Meter Diameter Parabolic Telescope (Resolution=8 to 15 cm from LEO)
- Simple Reliable Safe
- Simplicity, Reliability, Safety, Environmentally Clean
- High Launch Rate (All azimuth, On-demand)
- Less Than $500 of Electrical Power For Launch to LEO

Program Alliances



The Lightcraft Concept



- Three Main Components
  - Forebody Aeroshell (External Compression Surface)
  - Shroud (Air Inlet & Impulsive Thrust Surface)
  - Afterbody (Parabolic Mirror & Plug Nozzle)
- Tankage
  - Liquid Propellant (LN2, NH3 or LH2)
  - Helium Pressurant
- Nanosatellite (1 kg & 1 m Dia. Focus Telescope)
- Electronics in Forebody
- Reentry Capability
- Solar Powered in Orbit

APPLICATIONS

- Nanosatellite "low cost" launch on demand
  - Air Force, NASA, BMDO, Communication Industry
- High Resolution Imaging, Surveillance, and Mapping (~~i.e.,~~ e.g., Earth Resources)
- Global Positioning and Tracking
- Threat Detection and Tracking
- Astronomical Telescope (~~i.e.,~~ e.g., Amateur & Professional)
- Communications and Relay (~~i.e.,~~ e.g., Cellular Phone)
- Tactical Laser Propulsion (~~i.e.,~~ e.g., Hypersonic KKV)

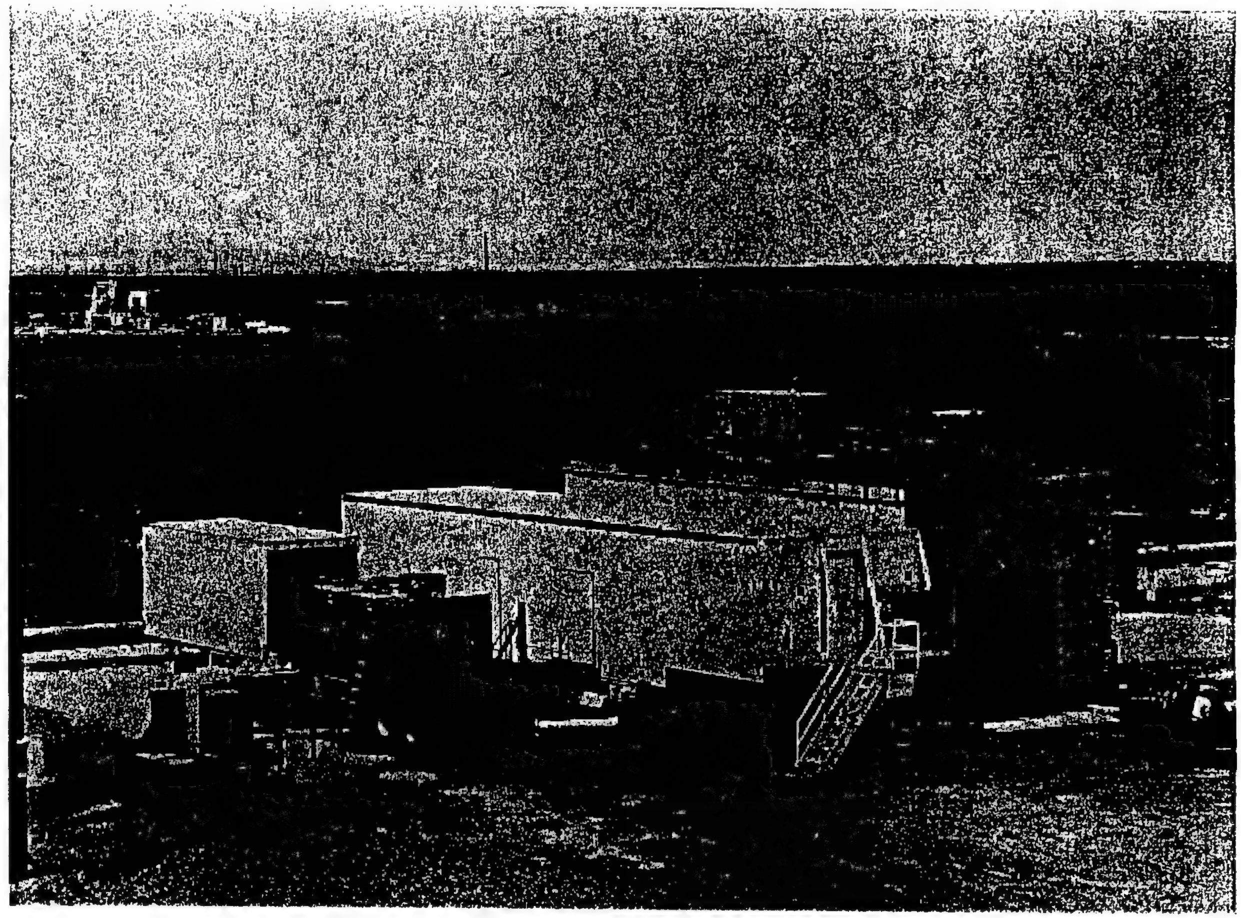
Lightcraft Development Objectives

- **Broad Application Based Nano-/Microsatellites**
  - **All Azimuth, Launch-on-demand** - don't need because it's not a complete sentence
  - **Air Force, NASA, BMDO, NRO, Communication Companies, Private Industry, Individuals**
- **Near-term (7 yrs.)**
  - **Launch to LEO of 1 kg vehicles for less than $500 of electrical power, and less than $20K total cost**
  - **Meet a variety of NASA/AF/Industry requirements for low cost access to space**
- **Far-term (10 to 12 yrs.)**
  - **Launch 100 kg (220 lbs) AF/NASA vehicles to LEO for less than $1.5M***
  - **Commercial laser launch services become viable contenders, as the lowest cost provider**

*** NASA requirement for Bantam-class payloads by FY 2006.**

Pulsed Laser Vulnerability Test System (PLVTS)

- **Original Performance**
  - 800 joules/pulse
  - 10 Hz 30-sec ?
  - 30 :sec pulses
- **Modified Performance**
  - 1998
    - 400 joules/pulse
    - 28 Hz 18-sec ?
    - 18 :sec pulses
  - 1999
    - 150 joules/pulse
    - 30 Hz 5-sec ?
    - 5 :sec pulses

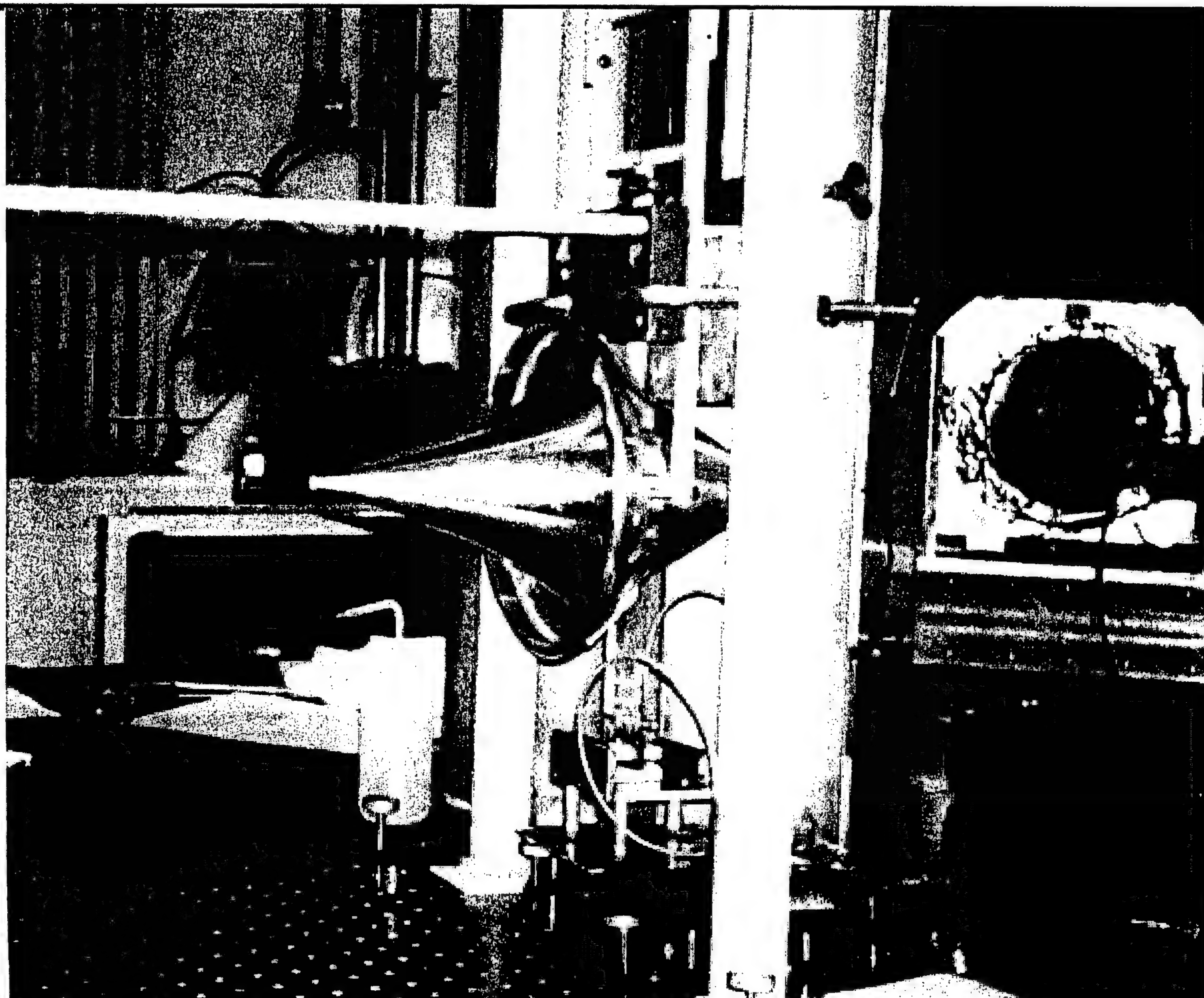


Phase I Accomplishments

- Phase I - Completed Dec 98
  - A 3-Year Program To Demonstrate Concept Feasibility
  - Lightcraft Concept Feasibility Demonstrated By:
    - Impulse, thrust, and pressure measurements accomplished.
    - Shadowgraph, and beam propagation (to ~90 m) studies accomplished.
    - Lightcraft optics/engine vehicle geometry optimized.
    - Pointing & tracking system demonstrated on horizontal wire-guided flights to ~122 m.
    - Out door vertical free-flights to ~29 m accomplished.

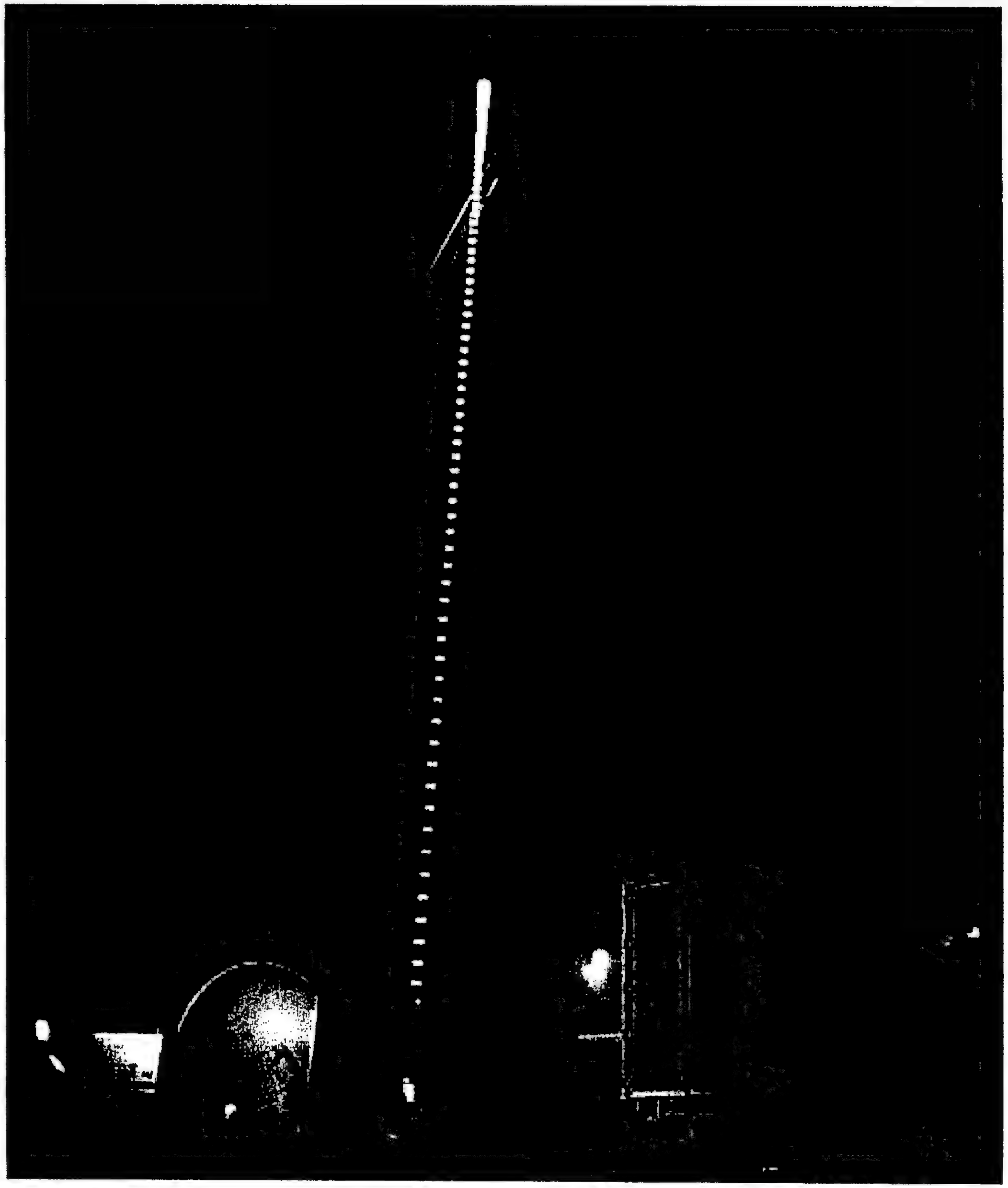
one word

Lightcraft Mounted to Ballistic Pendulum "Impulse Stand"

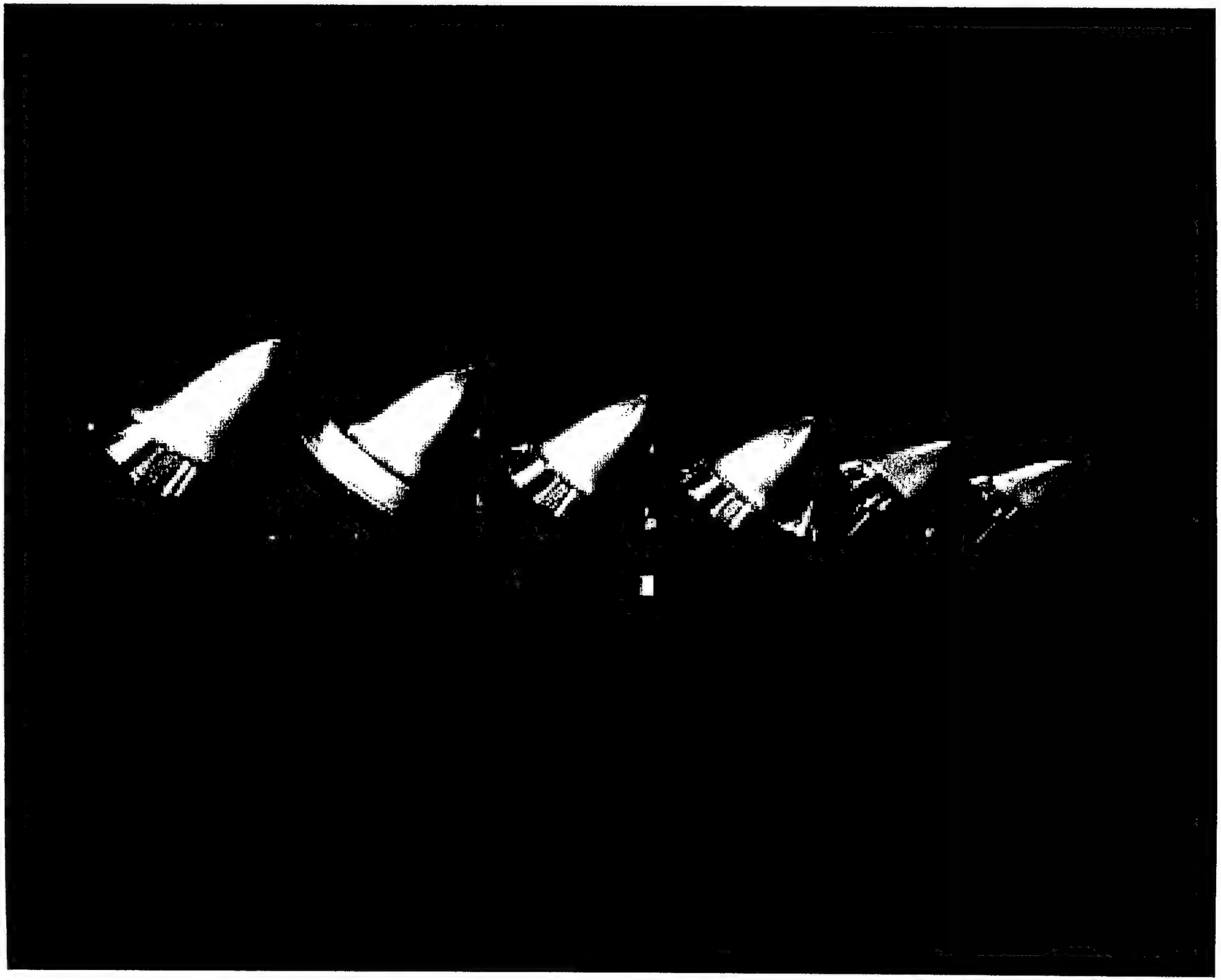


FOUR HUNDRED FOOT OUTDOOR WIRE TEST CONFIGURATION

29-Meter Outdoor Vertical Flight



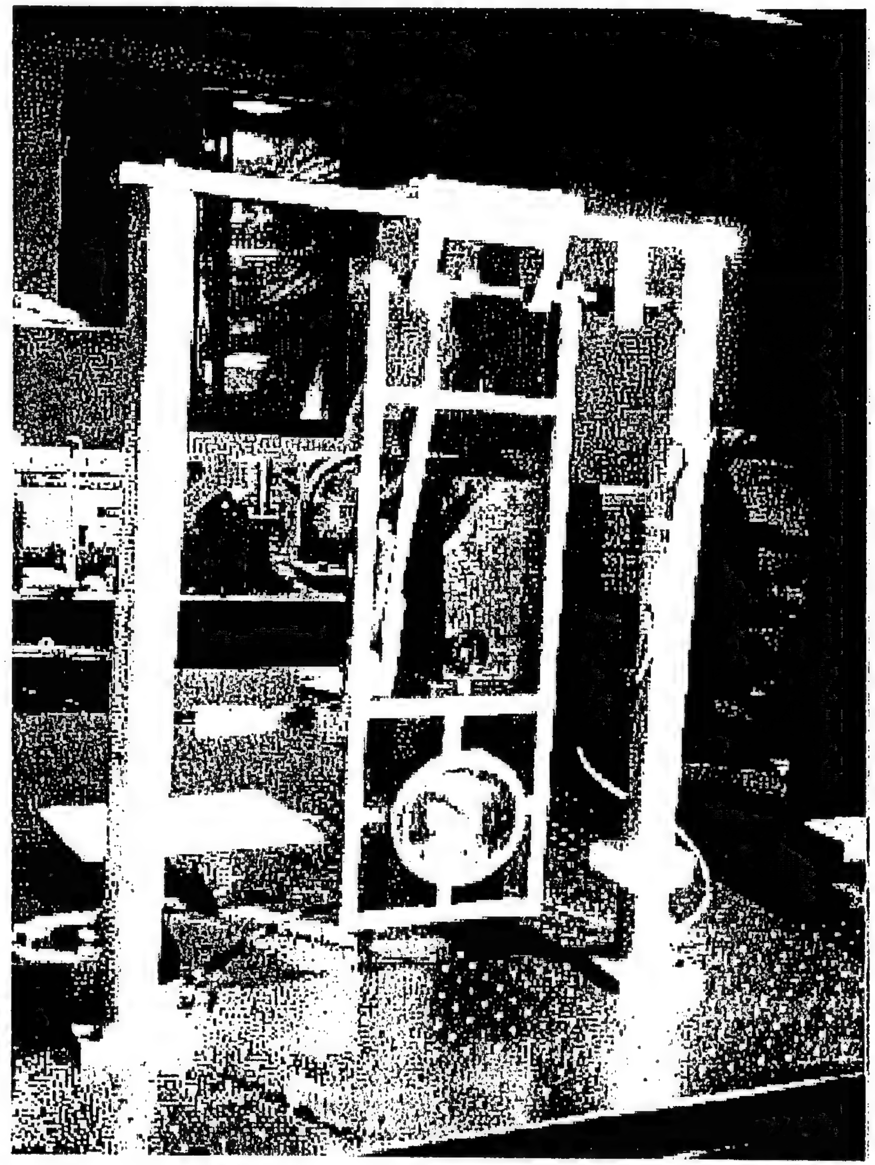
Model #200 Lightcraft Series



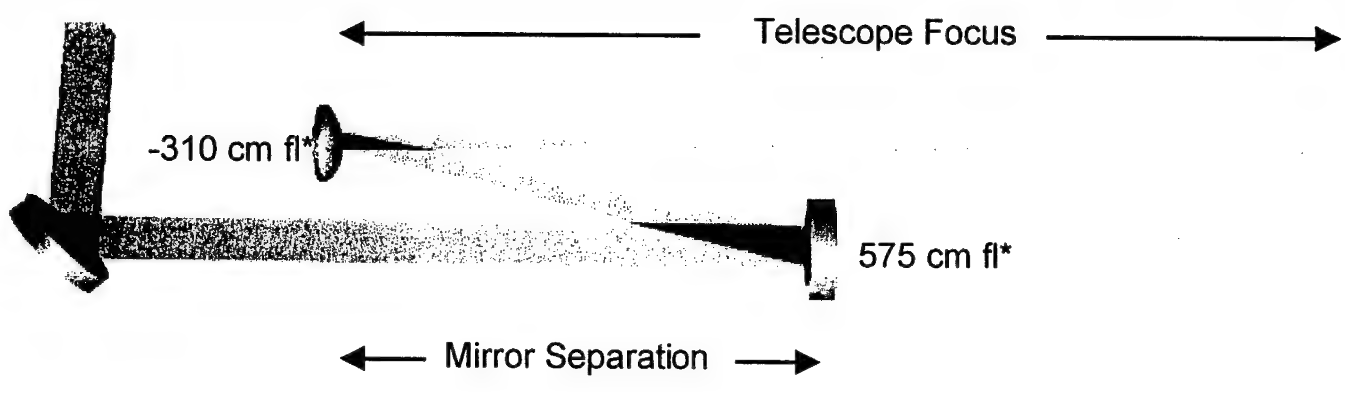
Phase II Accomplishments

- **Phase II – Initiated Jan 99**
  - A 5-Year Effort To Accomplish Vertical Launches to 30 km
  - With a 100 kW Laser. does this phrase go at the end of
  - Current Effort: Out Door Free Flight Tests To ~300 m.
    - Out door vertical free flights to ~40 m accomplished using
    - ablative fuel in near-field beam.
    - Lightcraft far-field beam performance measured with pendulum using
    - laboratory and FTT telescopes to ~533 m.
    - First, short (<1 m), vertical free flights conducted with
    - FTT telescope inside 500-meter building.
  - Continued Developments, Studies and Analyses
    - Characterize Model #200-3/4th with ceramic shroud.
    - Develop high temperature, lightweight ceramic optic with reflective
    - coating.
    - Continue flight dynamics and air inlet studies/design.
    - Obtain funding for 100 kW class CO_2 electric discharge laser.

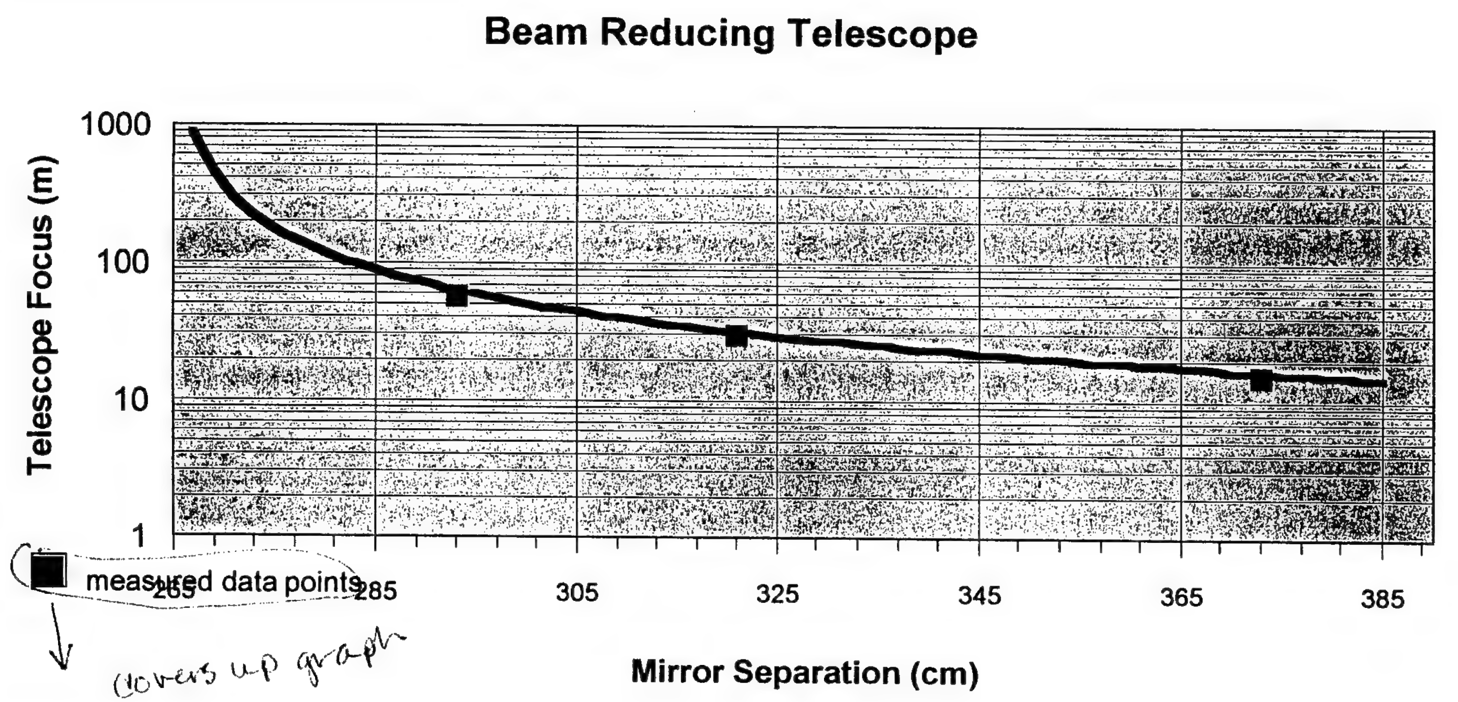
Pendulum Impulse Test Stand



Beam Reducing Telescope Used For Near Field Flights

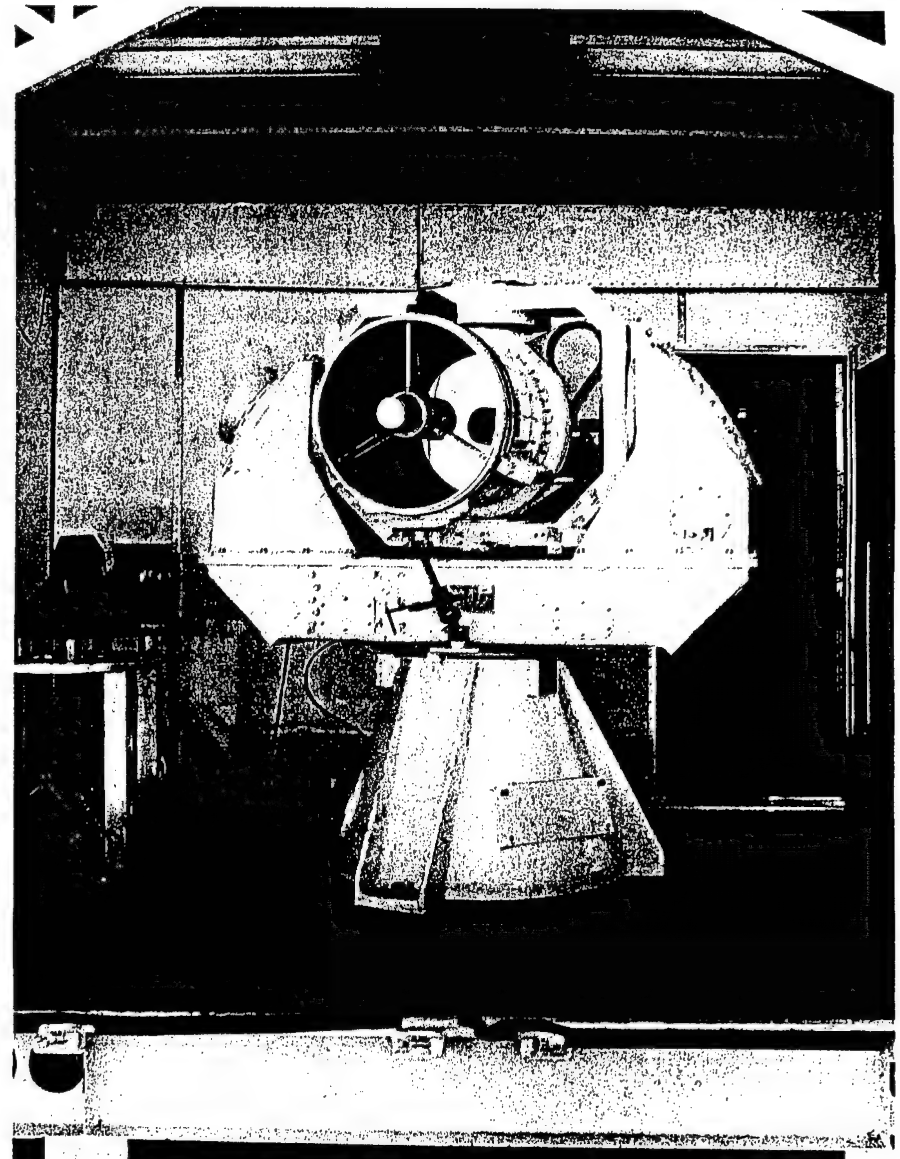


*focal lengths adjusted for curve fit

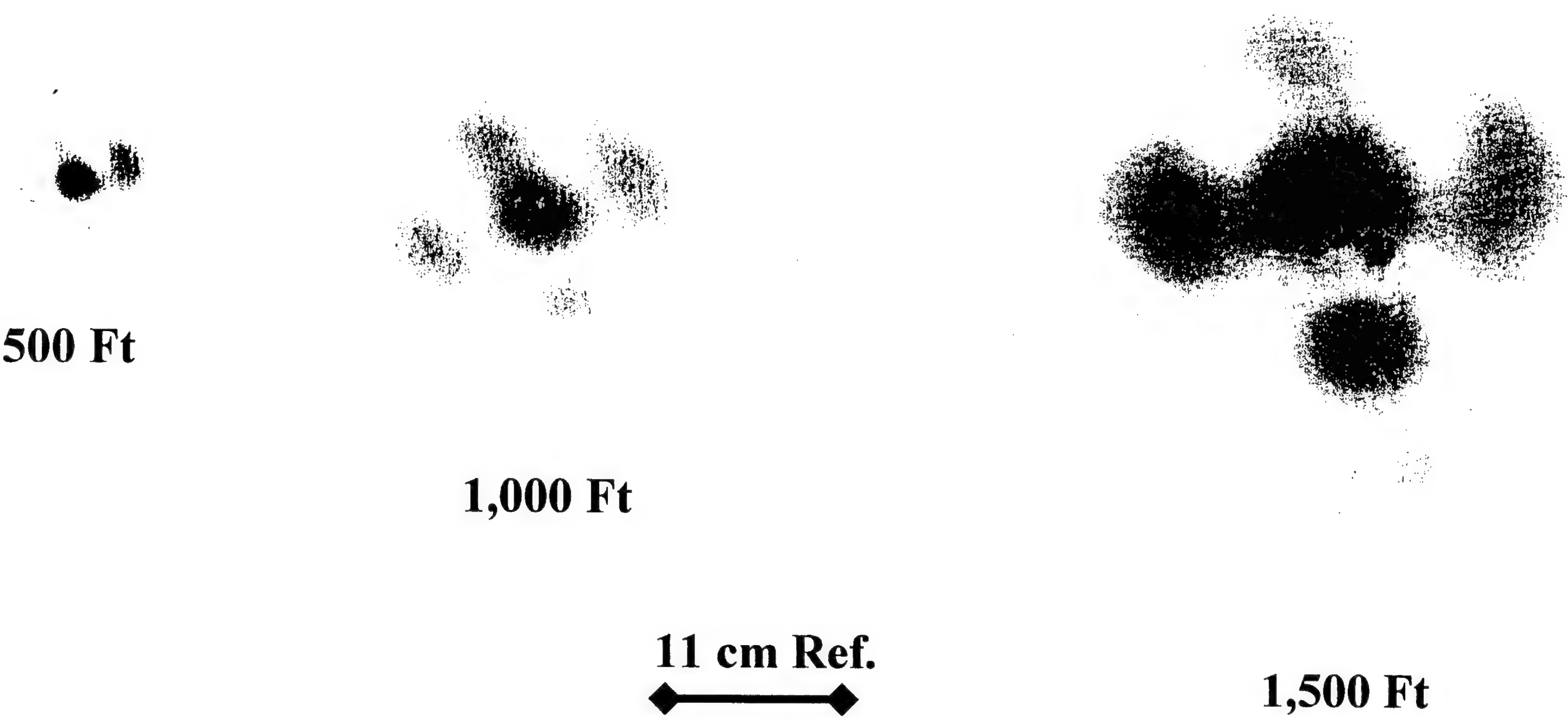


Field Test Telescope (FTT)

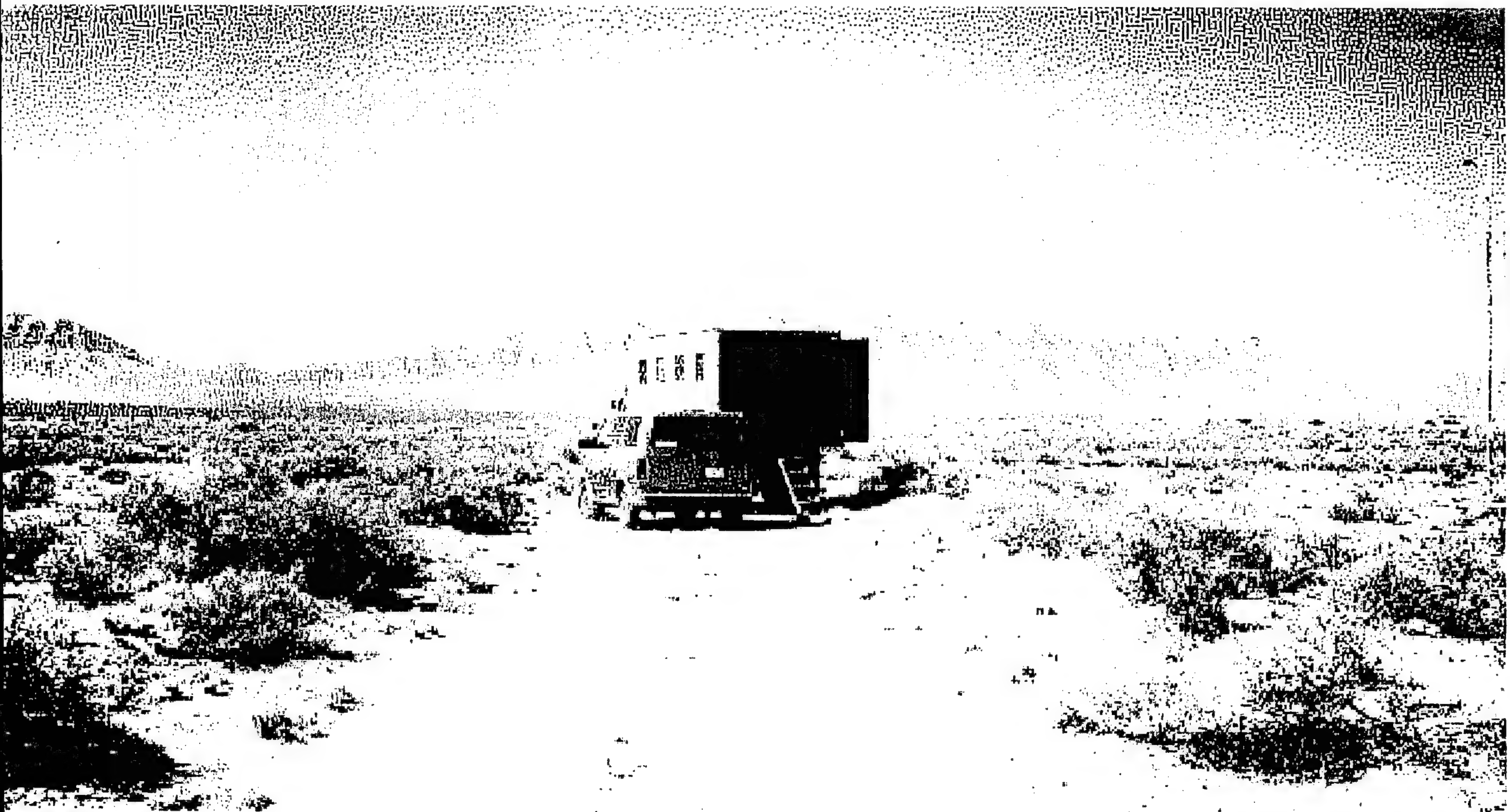
- **A Laser Beam Handoff to This Telescope Should Allow Flights to Altitudes of ~300 m (1,000 ft).**
  - **50 cm Diameter**
  - **Cassegrainian**
  - **Dynamic focusing**



FTT Beam Burn Patterns

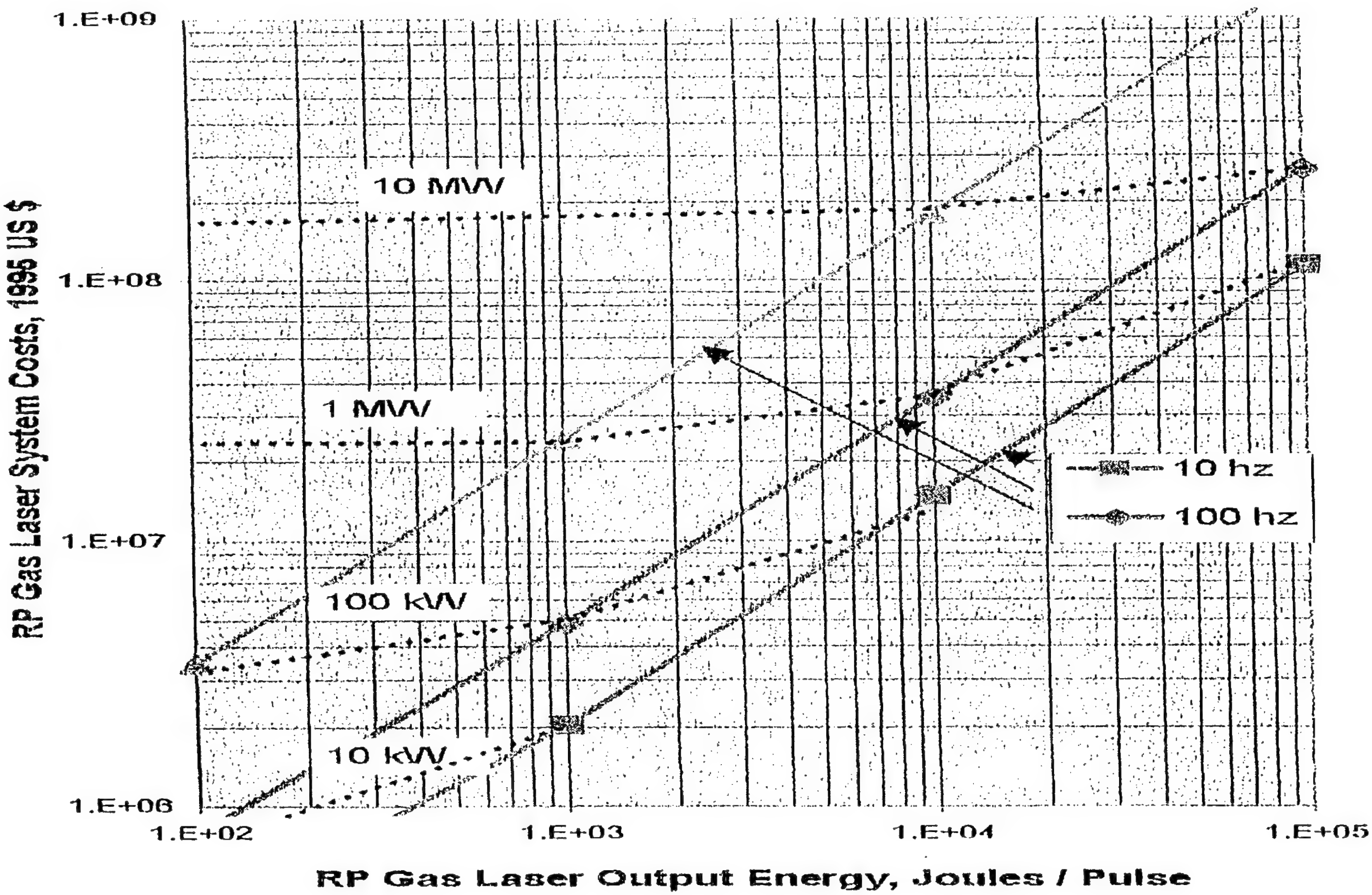


Optical Bench Set Up At 500-Ft Mark



RP GAS LASER COSTS (η = 10%)

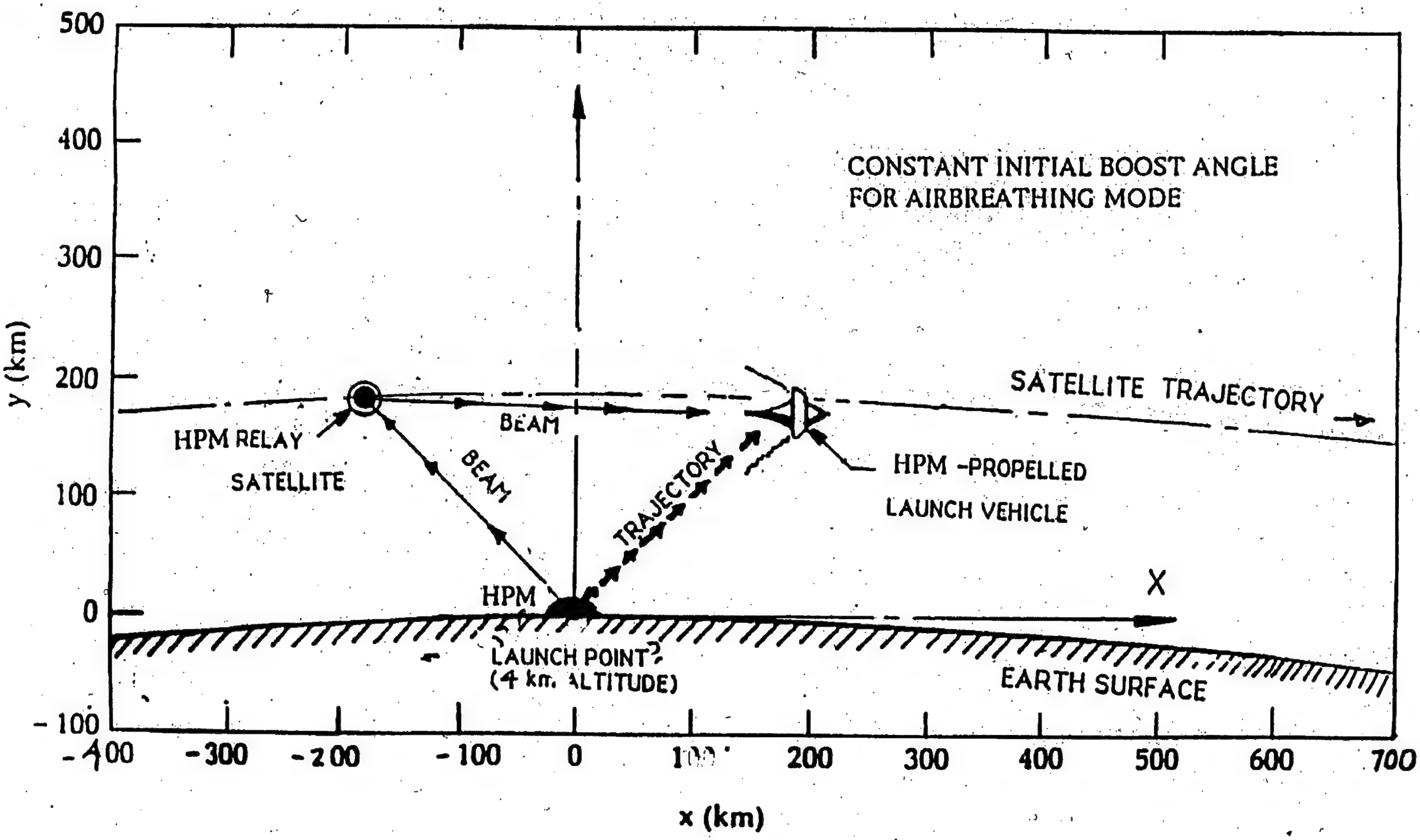
remove extra space



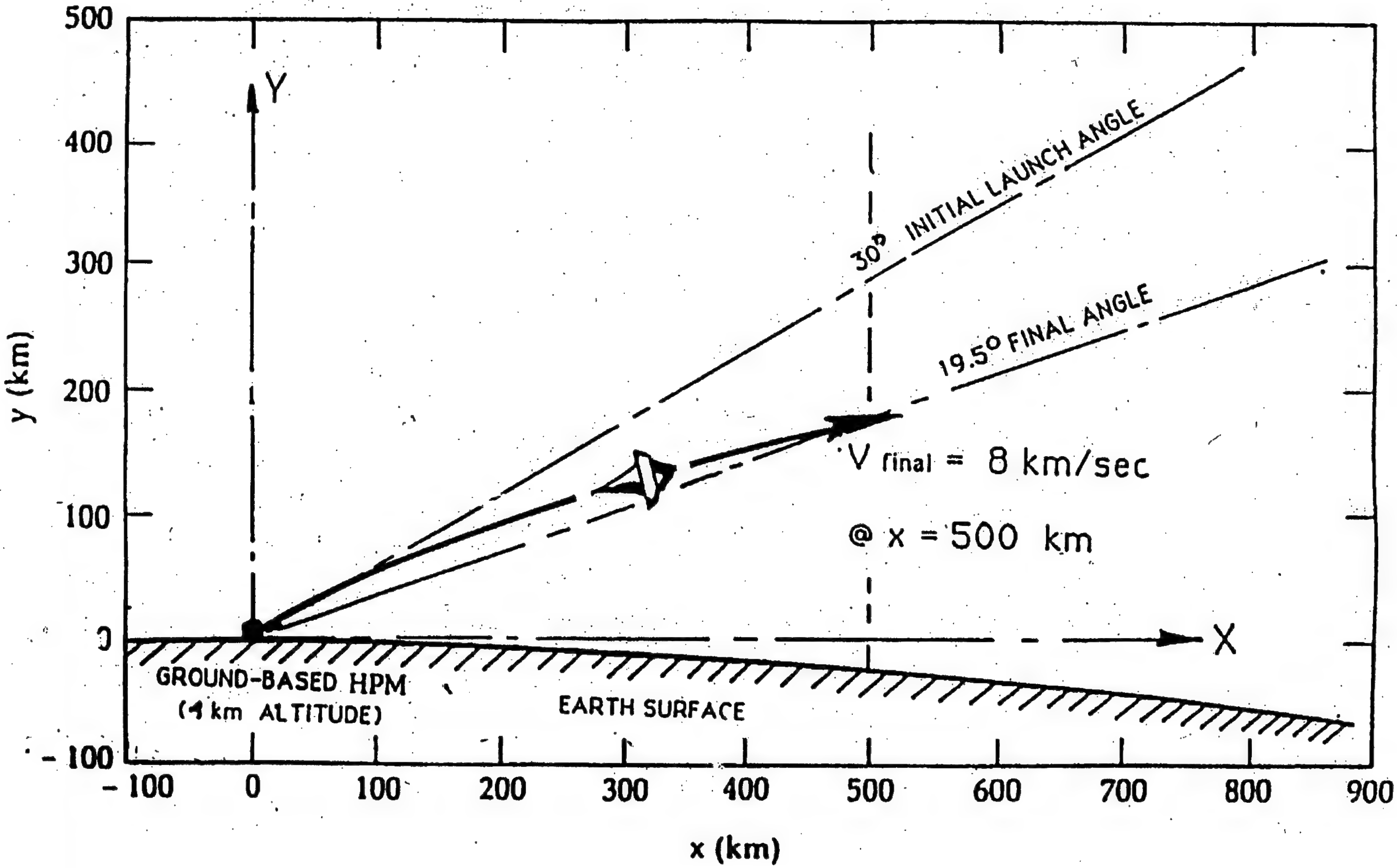
Introduction:
Rules of Thumb for a Laser Launch System

- **Payload to LEO: 1 kg/MW (within a factor of 2)**
- **Time to orbit: 400 to 1000 seconds**
- **Laser range required: 400 to 1500 km**
  - Longer ranges require space-based laser or relay mirror
- **Electrical energy per kg to LEO:**
  150 - 300 kW-hr / laser efficiency
- **Max. launch rate**
  - To any orbit: 4 - 8 per hour, 100 - 200 per day
  - To one plane at 28.5°: ~ 8 - 32 per day
  - To one plane at 90°: ~ 2 - 8 per day

Launch With Relay Satellite



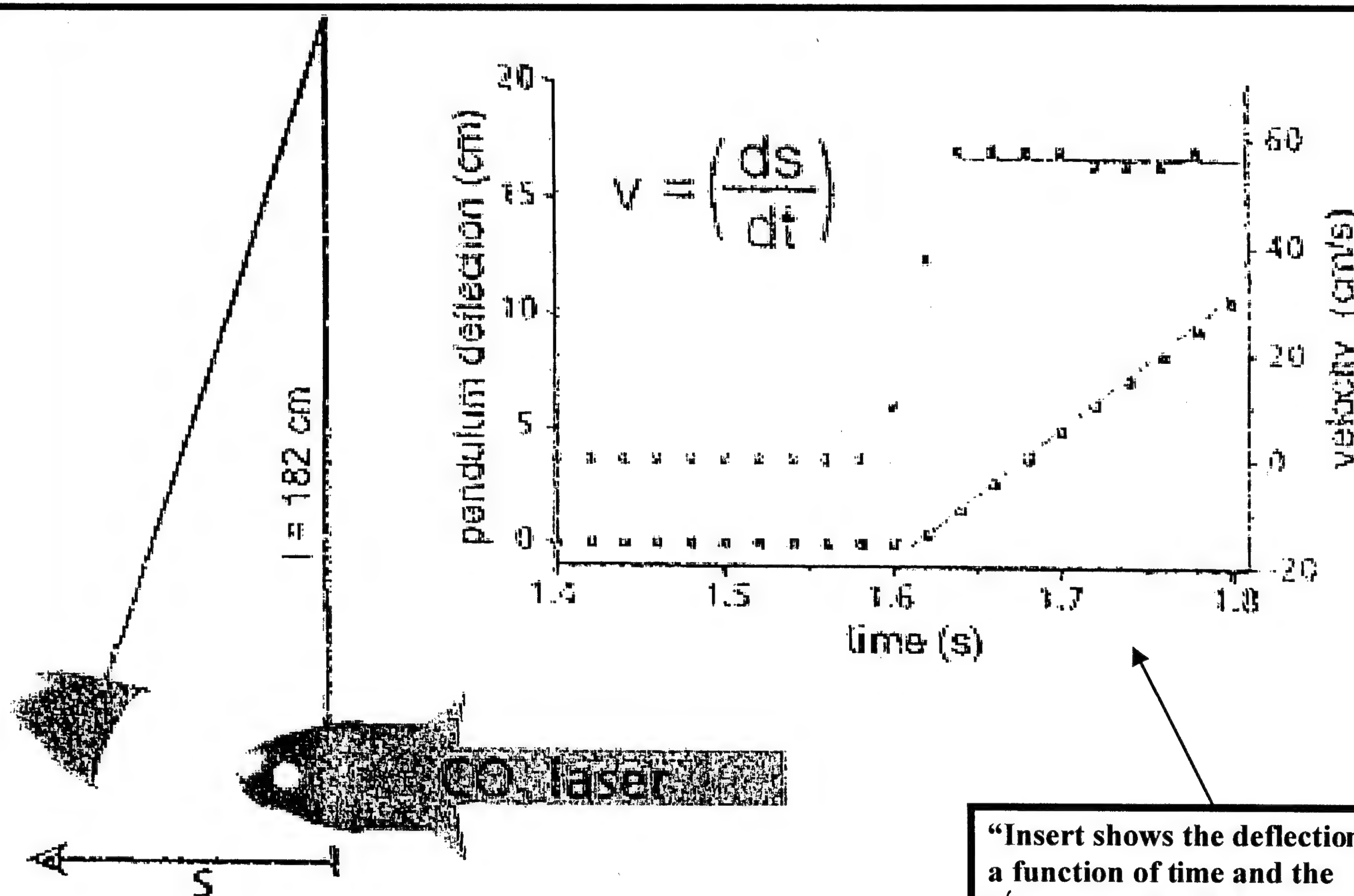
Direct Launch to Orbit (No Relay Satellite)



Laser Lightcraft Performance

A Paper By
Dr. Willy L. Bohn
DLR Institute of Technical Physics
D-70569 Stuttgart, Germany

Schematic Of Dr. Bohn's Pendulum Experiment*

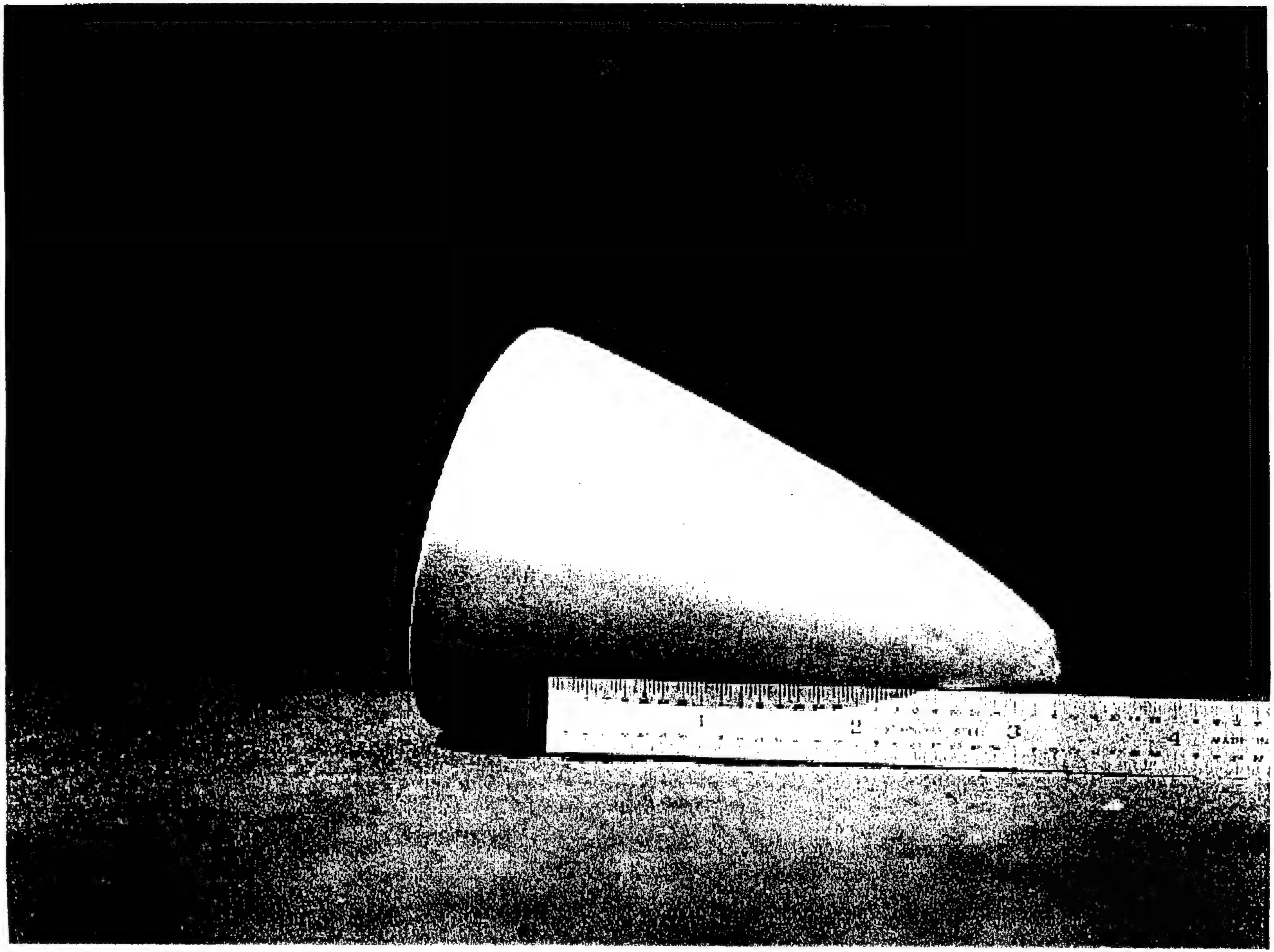


"Insert shows the deflection as a function of time and the Corresponding lightcraft velocity"

* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics

AVCO Pulsejet Test Thruster

(White Sands Missile Range, July 99)

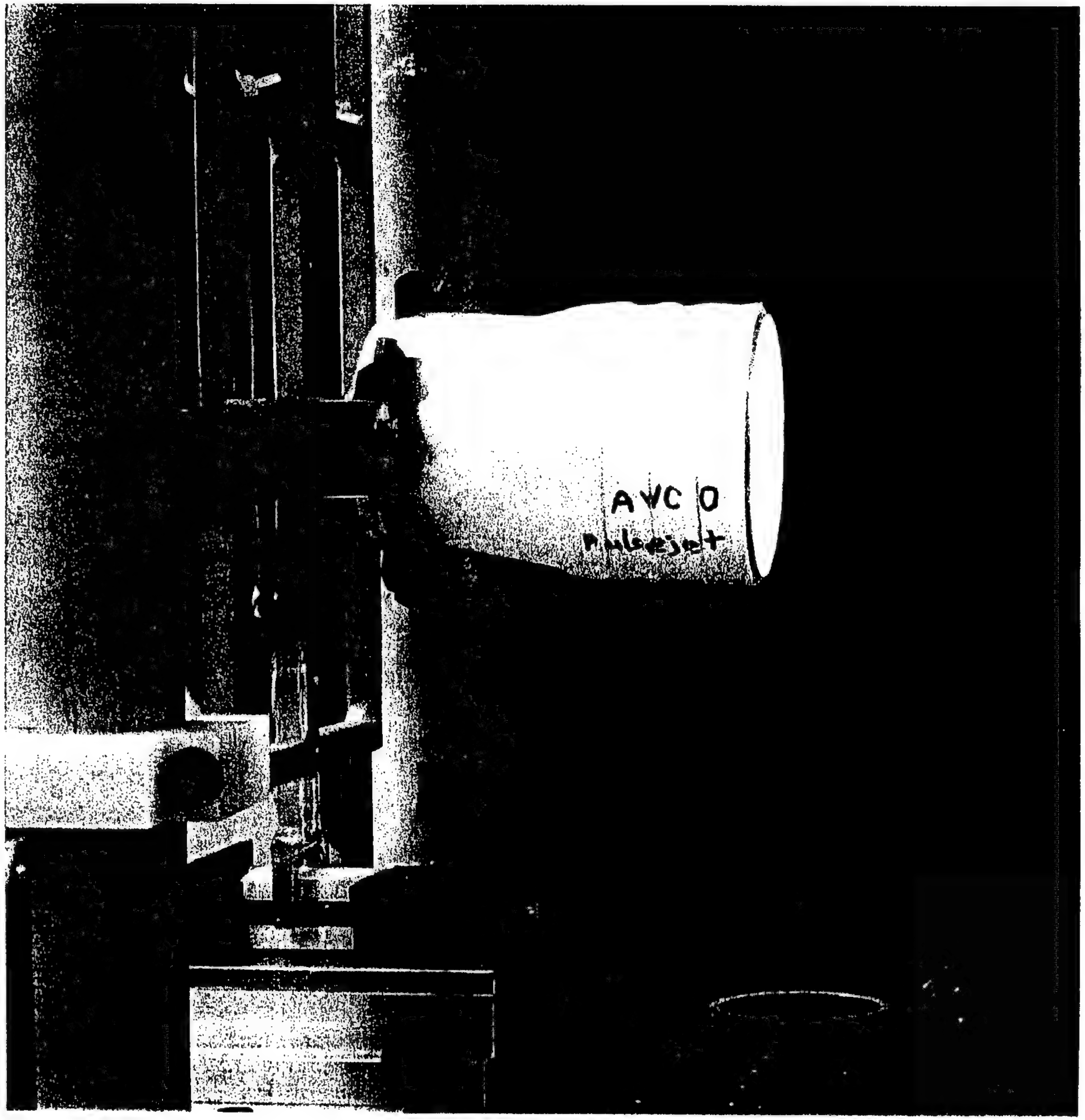


AVCO Pulsejet Test Thruster

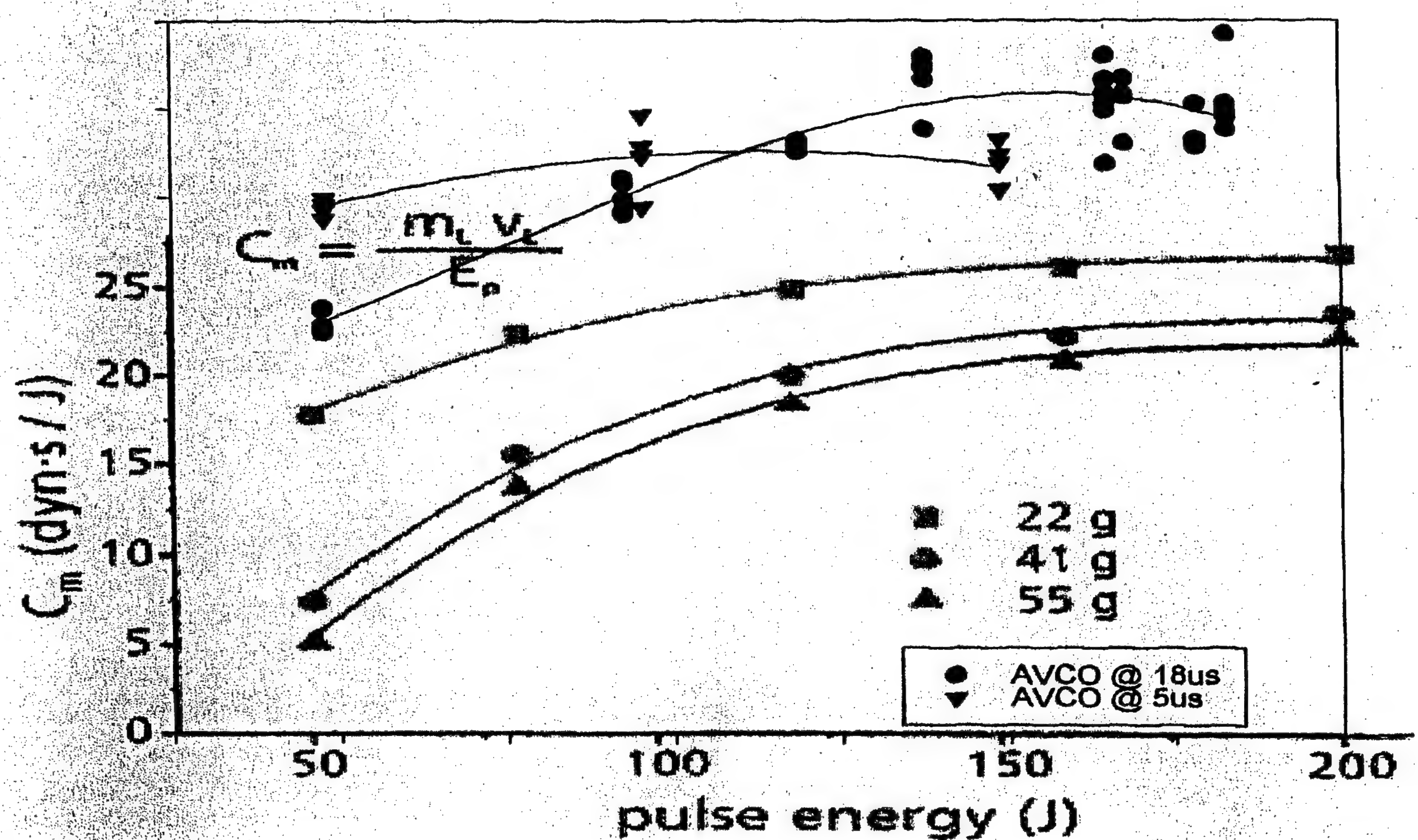
(White Sands Missile Range, July 99)

Test of AVCO Pulsejet Thruster Mounted on Pendulum Impulse Test Stand

(White Sands Missile Range, July 99)

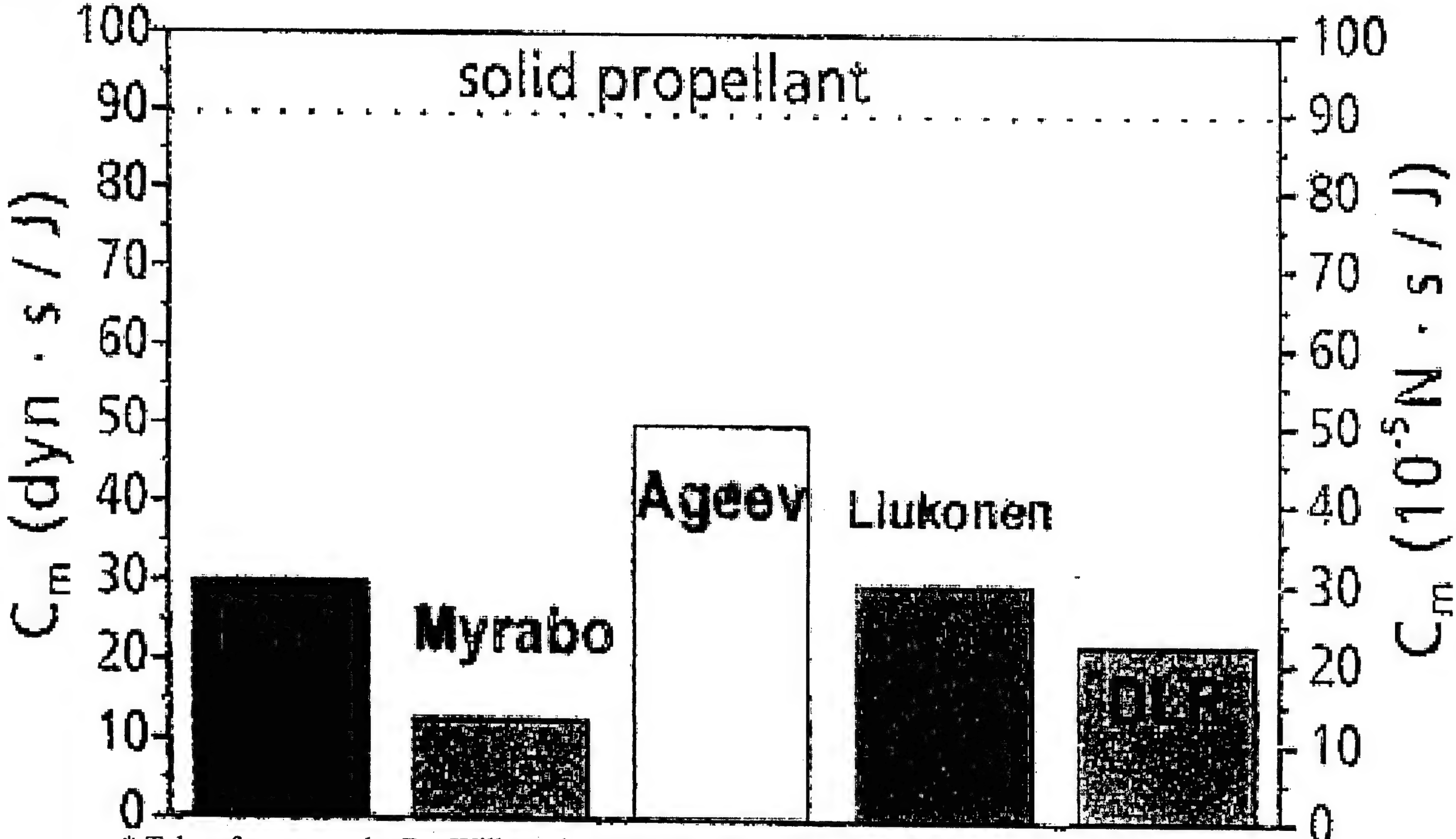


Comparison Of Dr. Bohn's Tests With AVCO Pulsejet Data Obtained At WSMR, July 99*



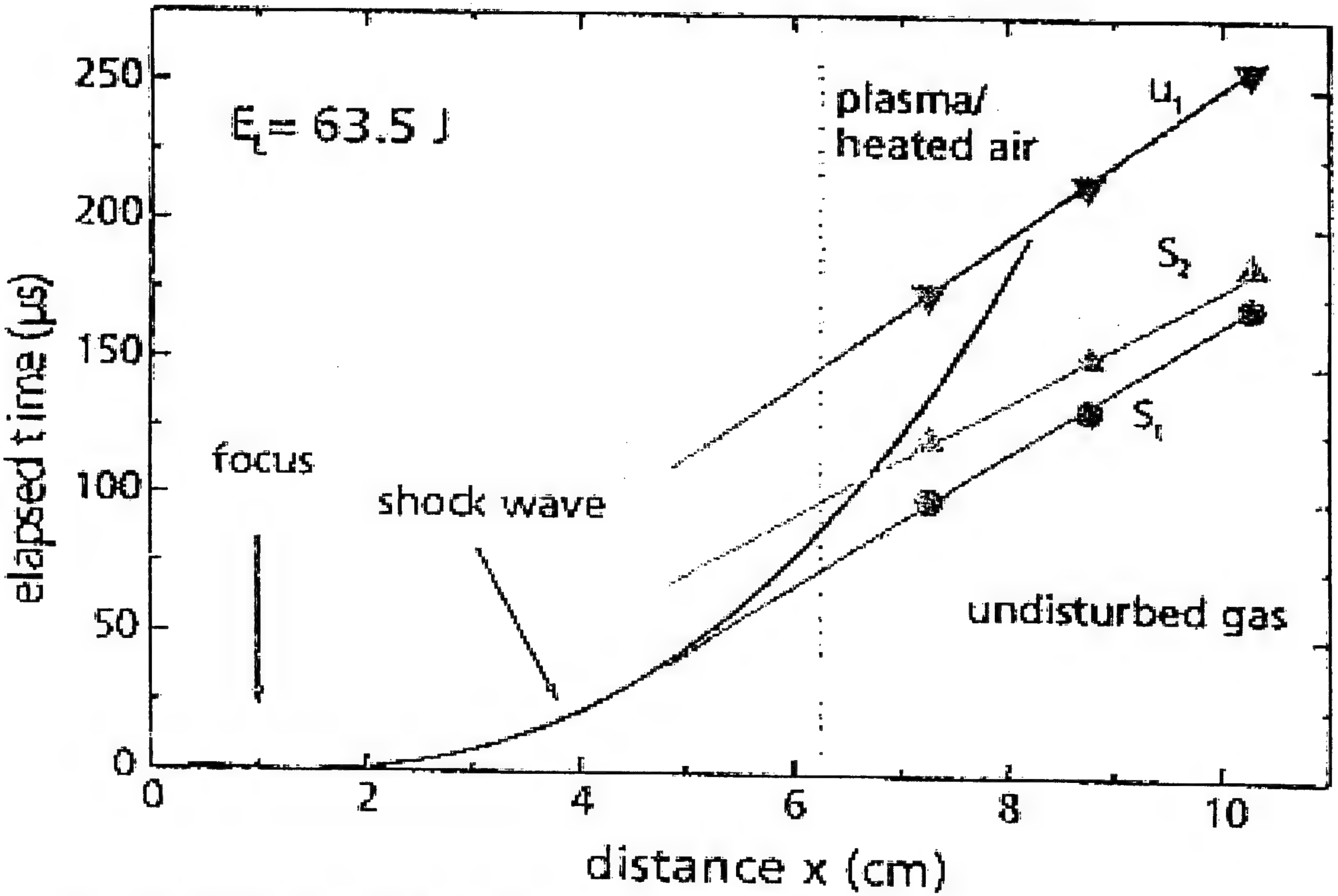
* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics

Comparison Of The Coupling Coefficient Obtained By Different Authors*



* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics

Evolution Of Shock Waves And Plasma In The Time-Space Domain*



* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics

Laser Propulsion Wrap-Up

- Many viable propulsion concepts possible using a laser source (mostly space propulsion)

- Laser propulsion system architecture cost dominated by laser source

- Promising near term concepts
  - Laser pulsejets (~~I.e.,~~ e.g., Lightcraft) and laser sail

*journal titles are italicized
*minimize use of abbreviat in references.

References

Laser Sails:

Marx, G., "Interstellar Vehicles Propelled by Terrestrial Laser Beam," Nature, 2 July 66, pp. 22-23.

Norem, P.C., "Interstellar Travel, A Round Trip Propulsion System With Relativistic Velocity Capabilities," A69-42829, American Astronautical Society Joint National Meeting, Denver CO, 17-20 Jun 69.

Redding, J.L., "Interstellar Vehicle Propelled by Terrestrial Laser Beam," Nature, 11 Feb 67, pp. 588-589.

Willinski, M.I., "Beamed Electromagnetic Power as a Propulsion Energy Source," ARS J., Aug 59, pp. 601-603.

*spell out names of places, centers, etc. which abbreviated!! (except laboratory can be abbreviated) journal? If so, italicize

Laser Propulsion:

*spell out 'Conference'

Anderson, J.L., Rather, D.G. and Powell, J.R., "Beamed Energy for Fast Space Transport," AIAA 96-2785, 32nd AIAA/ASME/SAE/ASEE Joint Propulsion Conf. erence, Lake Buena Vista FL, 1-3 Jul 96.

Arno, R.D., MacKay, J.S., and Nishioka, K., "Laser Energy Transfer - An Analytic Survey of High Power Applications," NASA, Advanced Concepts and Missions Div., OAST Moffett Field CA, 7th Intersociety Energy Conversion Conf. erence, 1972.

Bennett, H.E., "High Energy Laser Mirrors and Windows - Semi-Annual Report No. 5," Michelson ~~Lab~~. Laboratory (Lab.), Navel Weapons ~~Ctr~~. Center, China Lake CA, Sep 74.

Berggren, R.R. and Lenertz, G.E., "Feasibility of a 30-Meter Space Based Laser Transmitter," NASA CR-134903, Itek Corp. oration, Lexington MA, For NASA/LeRC, Oct 75.

Billman, K.W. (Ed.), "Proceedings of the Second NASA Conference on Laser Energy Conversion," NASA SP-395, NASA Ames Research ~~Ctr~~. Center, Moffett Field CA, 27-28 Jan 75.

Billman, K.W. (Ed.), "Proceedings of the Laser-Energy Conversion Symposium," NASA TM X-62,269, Ames Research Center, Moffett Field CA, 18-19 Jan 73.

Birkan, M.A. (Ed.), "Proceedings - Workshop On Laser Propulsion," AFOSR-TR-88-1340, AFOSR/NA, Bolling AFB DC, 10 Feb 88.

Braun, W.G., "Technique for Measuring the Absorption Coefficient of a Plasma," The Review of Scientific Instruments, V. 36, No. 6, Jun 65, pp. 802-805.

Brown E.A. and Jones M.V., "High Energy Laser Technology Assessment," Volume I: The Technology Assessment - An Initial Study, Harry Diamond Lab., Adelphi MD, For Headquarters, Dept. of the Army, Washington DC, Jan 75.
Department (Dept.)

Caveny, L.H. (Ed.), "Orbit Raising and Maneuvering Propulsion: Research Status and Needs," Review Copies of Ch. 1, Progress in Astronautics and Aeronautics Series, AFOSR, Bolling AFB DC, 6 May 83.

Caveny, L.H. (Ed.), *Orbit-Raising and Maneuvering Propulsion Research Status and Needs,* Progress in Astronautics and Aeronautics, Vol. 89, American Institute of Aeronautics and Astronautics, Inc., New York NY, 1984.

Chapman, P.K. and Otis, J.H., "Laser Absorption Phenomena in Flowing Gas Devices - Final Report," AVCO Everett Research laboratory, Inc., Under Contract No. NAS3-18559, For NASA/LeRC, Jun 76.

Chodzko, R.A., Mason, S.B. and Cross, E.F., "Annular Converging Wave Cavity," SAMSO-TR-76-115, The Aerospace Corp., For Air Force Weapons Lab., 1 Jun 76.
oration

Dyson, F.J. and Perkins, F.W., "Jason Laser Propulsion Study, Summer 1977," JSR-77-12, Stanford Research Institute, Menlo Park CA, For ARPA, Dec 77.

Feldman, A. et al., "Optical Materials Characterization," NBS TN-993, National Measurements Lab., NBS, Washington DC, Feb 79.

Ferriter, N.M. and Winslow, A.M., "Calculated Intensity Threshold for the Maintenance of Laser-supported Detonation Waves With Various Electron Densities," TID-4500,UC-34a, Lawrence Livermore Lab., Livermore CA, 10 Jun 74.

Ferriter, N.M., et al., "Analysis of Efficient Impulse Delivery and Plate Rupture by Laser-Supported Detonation Waves," UCRL-51836, Lawrence Livermore Lab., Livermore CA, 2 Jun 75.

Forward, R.L., "Advanced Propulsion Concepts Study - Comparative Study of Solar Electric and Laser Electric Propulsion," Hughes Research Lab., Malibu CA, For NASA/JPL, Jun 75.

Fowler, M.C., Newman, L.A. and Smith, D.C., "Beamed Energy Coupling Studies," AFRPL-TR-79-51, United Technologies Research Center, East Hartford CT, For AFRPL, Sep 79.

Fowler, M.C. et al., "Laser Supported Absorption Waves," N921716-9, United Aircraft Research Laboratories, East Hartford CT, For ARPA, Mar 74.
(Labs.)

Fowler, M.C. et al., "Laser Supported Absorption Waves," N921716-7, United Aircraft Research Lab., East Hartford CT, Jan 74.
Laboratories Labs.

Frisbee, R.H., Horvath, J.C. and Sercel, J.C., "Space-Based Laser Propulsion for Orbital Transfer," JPL D-1919, Jet Propulsion Lab., Pasadena CA, Dec 84.

Harris, E.L. and Glowacki, W.J., "Absorption of CO Laser Radiation by Water Vapor Near 5 µm," NOLTR 73-206, Naval Ordnance Lab., Silver Spring MD, 26 Nov 73.

Holmes, B.S. et al., "The Mechanical Loads From LSD Waves And Their Simulation, AFWL-TR-75-285, V. I (Analysis and Pressure Measurements), Air Force Weapons Laboratory, Kirtland AFB NM, For ARPA, Jul 76.

Howgate, D.W., Roberts, T.G. and Gerry, E.T., "New Laser Concepts - Executive summary Report," U.S. Army Missile Research and Development Command, Redstone Arsenal AL, Nov 77.

Huberman, M. et al., "Investigation of Beamed Energy concepts for Propulsion," AFRPL-TR-76-66, Vols. I & II, TRW Defense and Space Systems Gp., For AFRPL, Edwards AFB CA, Oct 76.

Jeng, San-Mou and Keefer, D., "A Theoretical Evaluation of Laser Sustained Plasma Thruster Performance," AIAA-87-2166, AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conf., San Diego CA, 29 Jun-2 Jul 87.
erence

Jeng, San-Mou and Keefer, D., "Influence of Laser Beam Geometry and Wavelength on Laser-Sustained Plasmas," AIAA-87-1409, AIAA 19th Fluid Dynamics, Plasma Dynamics and Lasers Conf., Honolulu HA, 8-10 Jun 87.
erence

Jeng, San-Mou and Keefer, D., "Numerical Study of Laser-Sustained Hydrogen Plasmas in a Forced Convective Flow," J. Propulsion, Jun 89, pp. 255-262.
italics

Jeng, San-Mou and Keefer, D., "A Theoretical Investigation of Laser-Sustained Plasma Thruster," AIAA-87-0383, AIAA 25th Aerospace Sciences Meeting, Reno NV, 12-15 Jan 87.

Jeng, San-Mou et al., "Numerical Study of Laser-Sustained Argon Plasmas in a Forced Convective Flow," AIAA-86-1078, AIAA/ASME 4th fluid Mechanics, Plasma dynamics and Lasers ~~Conf.~~, Atlanta GA, 12-14 May 86.
Conference

Jeng, San-Mou and Keefer, D., "Numerical Study of Laser-Sustained Hydrogen Plasmas in a Forced Convective Flow," AIAA-86-1524, AIAA/ASME/SAE/ASEE 22nd Joint Propulsion Conf., Huntsville AL, 16-18 Jun 86.
erence

Jones, W.S., Forsyth, J.B. and Skratt, J.P., "Laser Rocket System Analysis," NASA CR 159521, Lockheed Missiles & Space Co., For NASA/LeRC, 15 Mar 79.
mpany

Jones, W.S. et al., "Laser Power Conversion System Analysis," NASA CR 159523, Vols. I & II, Lockheed Missiles & Space Co., For NASA/LeRC, 15 Mar 79.
mpany

Kantrowitz, A., "Propulsion to Orbit by Ground-Based Lasers," Astronautics & Aeronautics, May 72, pp. 74-76. italics

Kare J.T., "Laser-Powered Heat Exchanger Rocket for Ground-To-Orbit Launch," UCRL-JC-110910, Lawrence Livermore National Lab~~oratory,~~ Livermore CA, 7 Jul 92.

Kare J.T., "Development of Laser-Driven Heat Exchanger Rocket for Ground-to-Orbit Launch," UCRL-JC-111507, Lawrence Livermore National Lab~~oratory~~, Livermore CA, 31 Aug 92.

Kare J.T., "Laser-Powered Heat Exchanger Rocket for Ground-to-Orbit Launch," J. Propulsion & Power, V. 11, No. 3, May-Jun 95, pp. 535-543. italics

Keefer, D. et al., "Laser Thermal Propulsion," Reprint from *Orbit-Raising and Maneuvering Propulsion: Research Status and Needs*, 84, pp. 129-148.

Keefer, D.R., Henriksen, B.B. and Braerman, W.F., "Experimental Study of a Laser Sustained Air Plasma," BRL MR 2416, USA Ballistic Research Lab., Aberdeen Proving Ground MD, Oct 74.

Keefer, D., Jeng, S-M, and Welle, R., "Laser Thermal Propulsion Using Laser Sustained Plasmas," IAF-86-17S, 37th Congress of the International Astronautical Federation, Innsbruck, Austria, 4-11 Oct 86.

Keefer D.R., Smith, L.M. and Sudharsanan, S.I., "Abel Inversion Using Transform Techniques," ICALEO '86 Laser Applications Conf., Arlington VA, Nov 86.

Keefer, D., Welle, R. and Peters, C., "Power Absorption in Laser-Sustained Argon Plasmas," AIAA J., V. 24, No. 10, Oct 86, pp. 1663-1669.

Keefer, D. Welle, R. and Peters, C., "Power Absorption Processes in Laser-sustained Argon Plasmas," AIAA-85-1552, AIAA 18th fluid dynamics & Plasmadynamics & Laser conf., Cincinnati OH, 16-18 Jul 85. erence

Keefer, D., Crowder, H. and Peters, C., "Laser Sustained Argon Plasmas in a Forced Convection Flow," AIAA-85-0388, AIAA 23rd Aerospace Sciences Meeting, Reno NV, 14-17 Jan 85.

Keefer, D., "Picosecond Laser Breakdown Thresholds in Gases," AFOSR-86-0317, University of Tenn. Space Institute, Tullahoma TN, For AFOSR, 30 Sep 91. essee

Keefer, D., Peters, C. and Crowder, H., "A Re-examination of the Laser-Supported Combustion Wave," AIAA J., V. 23, No. 8, Aug 85, pp. 1208-1212.

Kemp, N.H. and Krech, R.H., "Laser-Heated Thruster - Final Report," NASA CR-161666 (PSI TR-220), NASA/MSFC, Marshall Space Flight Center AL, Sep 80.

Kemp, N.H. and Rosen, D.I., "Laser Propulsion," AIAA-84-1445, AIAA/SAE/ASME 20th Joint Propulsion Conf., Cincinnati OH, 11-13 Jun 84.
erence

Kemp, N.H. and Root, R.G., "Analytical Study of Laser Supported Combustion Waves in Hydrogen," NASA CR-135349 (PSI TR-97), NASA/LRC, Cleveland OH, Aug 77.

Kemp, N.H. et al., "Laser-Heated Rocket Studies," NASA CR-135127 (PSI TR-53), NASA/LRC, Cleveland OH, May 76.

Kemp, N.H. and Lewis, P.F., "Laser-Heated Thrusters - Interim Report," NASA CR-161665 (PSI TR-205), NASA/MSFC, Marshall Space Flight Center AL, Feb 80.

Klosterman, E.L. and Byron, S.R., "Experimental Study of Subsonic Laser Absorption Waves - Final Report," AFWL-TR-74-3, Mathematical Sciences Northwest, Inc., For ARPA, Mar 75.

Krier, H., et al., "Energy Conversion Measurements in Laser-Sustained Argon Plasmas for Application to Rocket Propulsion," Annual Technical Report Submitted to AFOSR, Dept. of
niversity
Mechanical and Industrial Engr., U. of Illinois, Urbana-Champaign, Apr 88.
Engineering

Marcus, S. et al., "Laser Heating of Metallic Surfaces," LTP-31, Lincoln Lab., For DARPA, 20 May 76.

Mazumder, J., Rockstroh, T.J., and Krier, H., "Spectroscopic Studies of Plasma During CW Laser Gas Heating in Flowing Argon," J. Appl. Phys. **62** (12), 15 Dec 87.
italics

Mead, F.B., Jr. (Ed.), "Advanced Propulsion Concepts - Project Outgrowth," AFRPL-TR-72-31, Air Force Rocket Propulsion Lab., Edwards AFB CA, Jun 72.

Minovitch, M.A., "Reactorless Nuclear Propulsion - - The Laser Rocket," AIAA Paper No. 72-1095, AIAA/SAE 8th Joint Propulsion Specialist Conf., New Orleans LA, 29 Nov - 1 Dec 72.
erence

Minovitch, M.A., "Performance Analysis of a Laser Propelled Interorbital Transfer Vehicle," NASA CR-134966, Phaser Telepropulsion, Inc., For NASA/LeRC, Feb 76.

Minovitch, M.A., "The Laser Rocket - A Rocket Engine Design Concept for Achieving a High Exhaust Thrust With High I_{sp}," TM 393-92, Jet Propulsion Lab., Pasadena CA, 18 Feb 72.

Minovitch, M.A., "Laser Rocket," Patent #3,825,211, 23 Jul 74.

Minovitch, M.A., "Reactorless Nuclear Propulsion - The Laser Rocket," AIAA Paper No. 72-1095, AIAA/SAE 8th Joint Propulsion specialist Conf., New Orleans LA, 29 Nov-1 Dec 72.
erence

Minovitch, M.A., "An Orbiting High Power Laser Weapon System for Defense Against Hostile ICBM's," TR 201-2, Phaser Telepropulsion, Inc., Los Angeles CA, 13 Aug 73.

Minovitch, M.A., "Orbiting Space Vehicles That Dip Into the Outer Atmosphere of a Natural Celestial Body to Collect and Liquify Gas for Rocket Propellant, Life Support and Other Space Operations, TR 101-3, Phaser Telepropulsion, Inc., Los Angeles CA, 17 Dec 72.

Minovitch, M.A., "Thrusting Maneuvers for Telepropelled Reusable Orbiting Space Tugs Drawing Power From One Earth-Based Transmitting Station," TR 101-9, Phaser Telepropulsion, Inc., 22 Jun 73.

Myrabo, L. and Ing, D., *The Future of Flight,* Baen Enterprises, 8-10 W. 36th St., New York NY, 1985.

Nebolsine, et al., "Pulsed Laser Propulsion - Final Report," PSI TR-108, Physical Sciences Inc., Woburn MA, Feb 78.

Pirri, A.N., Simons, G.A. and Nebolsine, P.E., "The fluid Mechanics of Pulsed Laser Propulsion - Final Report," PSI TR-60, Physical Sciences Inc., Woburn MA, Jul 76.

Pirri, A.N. and Monsler, M.J., "Propulsion by Absorption of Laser Radiation," AIAA Paper No. 73-624, AIAA 6th Fluid and Plasma Dynamics Conf., Palm Springs CA, 16-18 Jul 73.
erence

Pirri, A.N. and Weiss, R.F., "Laser Propulsion," AIAA Paper No. 72-719, AIAA 5th Fluid and Plasma Dynamics Conf., Boston MA, 26-28 Jun 72.
erence

"Preliminary Evaluation of Pulsed Weapons (PEPWEP): Appendices A, B, C, D, and E," Vol. II, Science Applications, Inc., Jun 75.

"Pulsed Laser Propulsion - A Program Status Presentation to DARPA," Physical Sciences Inc., 1 Aug 80.

Reilly, D.A. and Rostler, P.S., "Pre-Breakdown Laser Target Vaporization and Enhanced Thermal Coupling - Final Report," AVCO Everett Research laboratory, Inc., Under Contract No. N00014-73-C-0457, For ARPA, Aug 74.

Rice, D.K., "Absorption Measurements of Carbon Monoxide Laser Radiation by Water Vapor," NLSD 72-11R, Northrop Corp., Hawthorne CA, For ARPA, Jul 72.
oration

Rockstroh, T.J., and Jyotirmoy, M., "Spectroscopic Studies of Plasma During CW Laser Materials Interaction," J. Appl. Phys. **61** (3), 1 Feb 87.
ital

Rosen, D. et al., "Experimental and Theoretical Studies of Laser Propulsion Phenomenology - Interim Report," PSI TR-371, AFOSR, Bolling AFB, Washington DC, Mar 84.

Rosen, D.I., Kemp, N.H., and Miller, M., "Studies of a Repetitively-Pulsed Laser Powered Thruster," PSI TR-358, Physical Sciences Inc., Woburn MA, Jan 83.

Rosen D.I. et al., "Pulsed Laser Propulsion Studies," PSI TR-184, Physical Sciences Inc., Woburn MA, Oct 82.

Schriempf, J.T., "Response of Materials to Laser Radiation: A Short Course," NRL Report 7728, Naval Research Lab., Washington DC, 10 Jul 74.

Selph, C., "Overview of Laser Propulsion," Unpublished Paper, AFRPL, Edwards AFB CA, 19 Sep 86.

Shoji, J.M. and Larson, V.R., "Performance and Heat Transfer Characteristics of the Laser-Heated Rocket - A Future Space Transportation System," AIAA 76-1044, AIAA International Electric Propulsion Conf., Key Biscayne FL, 14-17 Nov 76.

Shoji, J.M., "Laser-Heated Rocket Thruster," NASA CR-135128, Rocketdyne Div., Rockwell International, For NASA/LeRC, May 77.

Smith, L.M. and Keefer, D.R., "The Fourier Optical Analysis of Aberrations in Focussed Laser Beams," Proceedings at SPIE's 30th Annual International Technical Symposium, San Diego CA, Aug. 86.

Taussig, R. et al., "Design Investigation of Solar Powered Lasers for Space Applications,"MSNW 79-1087/1090-1, Mathematical Sciences Northwest, Inc., For NASA/LeRC, May 79.

Walters, C.T. and Barnes, R.H., "An Investigation of Mechanisms of Initiation of Laser-Supported Assoprtion (LSA) Waves," Batelle, Columbus Lab., Columbus OH, For DARPA, Jun 74.

Walters, C.T., Barnes, R.H. and Beverly, R.E., III, "An Investigation of Initiation of Laser-Supported Absorption (LSA) Waves," Battelle, Columbus Lab., Columbus OH, Jan 75.

Welle, R.P. and Keefer, D.R., "Imaging of Continuum Emission for Diagnostics of Laser Sustained Plasmas," Proceedings of First International Laser Science Conf., Nov 85.

Welle, R.P., Keefer, D.R. and Peters, C., "Energy Conversion Efficiency in High-Flow Laser-Sustained Argon Plasmas," AIAA-86-1077, AIAA/ASME 4th Fluid Mechanics, Plasma Dynamics and Lasers Conference, Atlanta GA, 12-14 May 86.

Young, L.A., Woodroffe, J.A. and Bresssell, E.R., "Laser Effects Assessment Program," AVCO Everett Research laboratory, Inc., Under Contract No. DASG60-76-C-0059, For DARPA, Jan 78.

"Laser Lightcraft": quotes are different here than all the others

Jones, R.A. et al., "Experimental Investigation of an Axisymmetric Hypersonic Scramjet Inlet for Laser Propulsion," J. Propulsion & Power, V. 8, No. 6, 92, pp. 1232-1238.

italics

Jones, R.A. et al., “Experimental Investigation of a 3-D Scramjet Inlet for Laser Propulsion at Mach Numbers of 10 to 25 and Stagnation Temperatures of 800 to 4100° K,” AIAA 29th Aerospace Sciences Meeting, Reno NV, 7-10 Jan 91.

Kennedy, W.C. et al., “Acoustic Noise Generated by a Laser-Boosted Transatmospheric Spacecraft,” accepted for publication in *J. Propulsion & Power.*

Lyons, P.W. et al., “Experimental Investigation of a Unique Airbreathing Pulsed Laser Propulsion Concept,” AIAA Paper #91-1922, given at the AIAA/SAE/ASME 27th Joint Propulsion Conf., erence
24-26 Jun 91.

Mead, F.B., Jr., Myrabo, L.N. and Messitt, D.G., “Flight and Ground Tests of a Laser-Boosted Vehicle,” AIAA 98-3735, 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cleveland OH, 13-15 Jul 98.

Messitt, D.G. et al., “Computational vs. Experimental Performance of an Axisymmetric Hypersonic Inlet for Laser Propulsion,” AIAA Paper #91-25447, AIAA/SAE/ASME 27th Joint Propulsion Conf., 24-26 Jun 91, Sacramento CA.
erence

Minucci, M. and Myrabo, L.N., “Phase Distortion in a Propulsive Laser Beam Due to Aero-Optical Phenomena,” J. Propulsion and Power, V. 6, No. 4, Jul-Aug 90, pp. 416-425.
Italics

Moder, J.P. et al., “Laser-Energized MHD Generator for Hypersonic Electric Air-Turborockets,” AIAA-87-1816, AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego CA, 29 Jun-2 Jul 87.

Myrabo, L.N., “Advanced Beam-Energy and Field Propulsion Concepts,” BDM/W-83-225-TR, The BDM Corp., McLean VA, For NASA/JPL, 31 May 83
oration

Myrabo, L.N. et al., “Transatmospheric Laser Propulsion - The Lightcraft Technology Demonstrator,” Rensselaer Polytechnic Institute, Troy NY, For Lawrence Livermore National Lab. and the SDIO Laser Propulsion Program, 30 Jun 89.

Myrabo, L.N. et al., “Laser-Boosted Lightcraft Technology Demonstrator,” Proc. of the First International Conference on Hypersonic Flight in the 21st Century, Grand Forks ND, 20-23 Sep 88; ISBN No. 0-9608700-106. University of North Dakota, Department of Space Studies, Jan 89, pp. 353-365.

Myrabo, L.N. et al., “Transatmospheric Laser Propulsion,” Final Technical Report, prepared under Contract No. 2073803 for Lawrence Livermore National Laboratory and the SDIO Laser Propulsion Program, 30 Jun 89.

Myrabo, L.N., Messitt, D.G. and Mead, F.B., Jr., “Ground and Flight Tests of a Laser Propelled Vehicle,” AIAA 98-1001, 36th Aerospace Sciences Meeting & Exhibit, Reno NV, 12-15 Jan 98.

Myrabo, L.N. et al., "Monocle Shuttle: Strategic Applications of the RBR/FBR," BDM/W-82-671-TR, The BDM Corp., McLean VA, For DARPA, Dec 82.
oration

Myrabo, L.N., "Solar-Powered Global Air Transportation," AIAA 78-689, AIAA/DGLR 13th International Electric Propulsion Conference, San Diego CA, 25-27 Apr 78.

Nyberg, G.A. et al., "Performance Analysis of a Laser-Heated Single-Stage-to-Orbit Shuttlecraft," AIAA-87-1815, AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego CA, 29 Jun-2 Jul 87.

Powers, M.V., Zaretzky, C. and Myrabo, L.N., "Analysis of Beamed-Energy Ramjet/Scramjet Performance," AIAA-86-1761, AIAA/SAE/ASME/ASEE 22nd Joint Propulsion Conference, Huntsville AL, 16-18 Jun 86.

Strayer, T.D. et al., "Investigation of Beamed-energy ERH Thruster Performance," AIAA-86-1760, AIAA/SAE/ASME/ASEE 22nd Joint Propulsion Conference, Huntsville AL, 16-18 Jun 86

Walton, D., List, G.F. and Myrabo, L.N., "Economic Analysis of a Beam-Powered Global Aerospace Transportation System," AIAA-89-2443, AIAA/ASME/SAE/ASEE 25th Joint Propulsion Conference, Monterey CA, 10-12 Jul 89.

NASA Lightcraft Propulsion:

Phipps, C.R., "NASA Design Study: Optimized Parameters for Laser Space Propulsion," Photonic Associates, Santa Fe NM, For NASA/MSFC, 15 Dec 99.

Phipps, C.R. et al., "Enhanced Vacuum Laser-Impulse Coupling by Volume Absorption at Infrared Wavelengths," Laser and Particle Beams (1990), vol. 8,no. 1-2, pp. 281-298.

Phipps, C.R. and Michaelis, M.M., "LISP: Laser Impulse Space Propulsion," Laser and Particle Beams (1994), vol. 12, no. 1, pp. 23-54.